# Quantum Computing Hardware Implementation Methods: A Survey over Categories

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***Abstract*— In this paper, we conduct a comprehensive survey of quantum hardware implementation methods with an assessment to categorize them, manifest them under an even scheme, and indicate their weaknesses, strengths, differences and similarities. Those quantum hardware implementation methods are categorized into five groups according to the basic elements they are using: Nuclear Magnetic Resonance (NMR), ion traps, all optical, super conducting, and quantum dots. We compare these methods to indicate the method with the most promising potential.**

***Index Terms*—Quantum computing, hardware, nuclear magnetic resonance, ion traps, all optics, super conducting, quantum dots.**

## I. INTRODUCTION

Why build a quantum computer? Because it's not there, since the implementation of quantum computing machines represents a formidable challenge to the communities of engineers and applied physicists. However, there is some hope in sight: quite recently, some simple quantum devices consisting of a few qubits have been successfully built and tested.

Different implementation methods are used including ion traps, Nuclear Magnetic Resonance (NMR) spectroscopy, optics, Josephson junction, and quantum dots. In this paper, we survey a variety of proposed quantum computing quantum hardware implementation methodologies using the taxonomy framework proposed by Van Meter, 2006 in [1].

This paper structure is as follows: quantum hardware implementation methods are discussed in section II. The different implementation methods categories are discussed in the subsections of that section. Finally, we provide the conclusions in section III.

## II. QUANTUM HARDWARE IMPLEMENTATION METHODS

Despite the experimental problems of implementing quantum devices, theoretical physicists have tried to conceive some implementations for quantum algorithms. We present five technologies: NMR, ion traps, all optical, super conducting, and quantum dots. These systems were chosen for their near and long term implementation capabilities. In the following subsections, we will briefly discuss each technology and its architectural implications.

### *A. NMR*

Nuclear Magnetic Resonance (NMR) quantum computing uses the spin states of molecules as qubits. NMR differs from other implementations of quantum computers in that it uses an ensemble of systems, i.e. molecules. The ensemble is initialized to be the thermal equilibrium state. In mathematical parlance, this state is given by the density matrix [2]:

$$\rho = \frac{e^{-\beta H}}{\mathrm{Tr}\left(e^{-\beta H}\right)},$$

where H is the Hamiltonian matrix of an individual molecule and

$$\beta = \frac{1}{kT}$$

where *k* is the Boltzmann constant and *T* the temperature.

In the following subsections, we will go through solution NMR, All-Silicon NMR, and Kane Solid-State NMR.

### *1. Solution NMR*

Probably the most complete demos of quantum computation to date are the solution NMR experiments [3]. In an NMR system, the qubit is denoted by the spin of the nucleus of an atom. When placed in a magnetic field, that spin processes, and the spin can be deployed via microwave radiation. In solution NMR, a carefully planned molecule is used. Some of the atoms in the molecule have nuclear spins, and the frequency of radiation to which they are disposed varies depending on their position in the molecule, so that different qubits are addressed by frequency. Many copies of the molecule are held in a liquid solution; each molecule is a separate quantum computer, run independently, with the large numbers providing adequate signal strength for readouts. This is the canonical ensemble system [4].

| **Strengths** | **Weaknesses** |
|---|---|
| Good decoherence time, room temperature operation, and advanced experimental verification. | Slow gates, poor scalability, and difficult concurrent operations. |

### *2. All-Silicon NMR*

Ladd et al. have proposed an all-silicon NMR-based quantum computer which stores qubits in the nuclear spin of 29Si (spin 1/2 nucleus) laid down in a line across a micromechanical bridge of spin 0 nuclei (28Si and 30Si). This is an ensemble system; 105 copies are required to get satisfactory signal for measurement. Readout is done via magnetic resonance force microscopy (MRFM), reading oscillations of the bridge. Initialization is done via electrons whose spins are set with polarized light. Operations are done via microwave radiation directed at the device [1].

| **Strengths** | **Weaknesses** |
|---|---|
| Longest known decoherence time; | Slow gates, measurement still being designed. |

### *3. Kane Solid-State NMR*

Kane has suggested a solid-state NMR system with excellent scalability, built on VLSI techniques for control [6]. Then, others suggested that teleportation may be required to move qubits long distances even for error correction, and progress in fabrication has been made. In this system, individual phosphorus atoms are embedded in a silicon substrate, and standard photolithography techniques are used to build control structures on the surface. The qubit is held in the spin of the phosphorus nucleus, and interactions between neighboring qubits are mediated by electrons coupled to the nuclei via hyperfine interactions. The shape of the electron wave function is controlled via the control structures built on the Si surface; the distance between neighboring $P$ atoms and the accuracy of aligning the control gates to the $P$ impurities will determine the quality of qubit interactions.

| **Strengths** | **Weaknesses** |
|---|---|
| Long coherence time; | Difficult fabrication, creating adequate overlap in electron wave functions. |

## *B. Ion Trap*

One of the few systems that explicitly separate storage areas from interaction areas is the scalable ion trap [7]. In ion trap systems, qubits are usually stored in the energy levels of individual ions. Early ion trap experiments featuring small numbers of ions held in a single trap have given way to a large system of interconnected, individually controllable traps. In the scalable trap system, the ions are literally moved around using magnetic fields until they reach locations in the system designated for operations, as shown in Figure 3. Small numbers of ions are brought together and formed into chains to execute multi-qubit gates. Gates are effected by laser pulses, and readout is also accomplished by laser pulses creating fluorescence (interpreted as a 1) or not (0), depending on the state of the atom. Gate times are moderate; speed can be traded off against fidelity in the range of 14-100kHz. Overall system performance will likely be driven by ion movement times (which naturally depend on distance and topology), times for creating and splitting chains of atoms, time to cool atoms heated by the movement process, and multiplexing of gate operations. The movement operations are unlikely to allow a gate rate in excess of 20kHz.

| Strengths | Weaknesses |
|---|---|
| Scalability of storage; | Slow gates; limitations on concurrent operations and measurements. |

### *C.All Optical*

All-optical systems come in two flavors: those that depend on nonlinear effects to execute gates, and those in which the only necessary nonlinearity is measurement, known as Linear Optics Quantum Computation *(LOQC*). Research on all-optical systems has focused on photon sources capable of generating precise numbers of photons with the necessary timing precision, gates based on measurement, and high-quality single-photon detectors [11]. Measurement-based gates are inherently probabilistic in nature, though it has been shown that these gates can be built into a scalable feed-forward network. Much of the current experimental work is focusing on this approach, and individual gates have been shown to work.

Jitter and skew are likely to be managed by “stopped light,” created by electromagnetically-induced transparency.

| Strengths | Weaknesses |
|---|---|
| Well-understood physics and easy fabrication; | Photon losses; for nonlinear systems, weak nonlinear effects give poor gate quality; high resource requirements for probabilistic gates. |

### *D. Super Conducting*

Super conducting devices come in three flavors: represent qubits using charge, using flux, and using phase; most of the information in the tables applies to all three. Fabrication is done using conventional electron-beam lithography and shadow evaporation of Al onto a SiNx insulating substrate. In the charge qubit, a sub-micron size superconducting box (essentially, a small capacitor) is coupled to a larger superconducting reservoir. In a superconductor, electrons move in pairs known as Cooper pairs.

The qubit representation is the number of Cooper pairs in the box, controlled to be either zero or one, or a superposition of both. Similarly, for the flux qubit, Cooper pairs are introduced into a superconducting ring, where they circulate and induce a quantized magnetic flux. Because the flux qubit has slower gate times but a relatively even longer coherence time, experimental efforts appear to be shifting toward the flux qubit approach [1].

In one proposed scalable form of the charge qubit it is possible to address any two qubits and couple them. This is done through a shared inductance. In this case, the restriction of operations involving only neighboring qubits in a linear array is removed, but execution is limited to one gate at a time.

A different proposal links neighboring qubits in a one-dimensional structure with nearest-neighbor-only gates, but potentially may allow concurrent gates on independent qubits.

| Strengths | Weaknesses |
|---|---|
| Very fast gates, advanced experimental demonstration, straightforward fabrication. | Low coherence time relative to measurement time, sensitivity to background charge fluctuations and local magnetic fields. |

### *E. Quantum Dot*

A “quantum dot,” as used in quantum information processing, is a lithographically-defined structure that confines electrons at the boundary layer between two materials, creating a two-dimensional electron gas (2DEG). By varying the surrounding electrical potential, individual electrons can be positioned in a small area, called the quantum dot. A qubit can be defined based on the number of electrons in a quantum dot or the spin or energy levels of a single electron held in a quantum dot. Several quantum dot devices are under development; one experimentally advanced approach uses a pair of quantum dots as a dual-rail encoded logical qubit, with a single electron in the left dot representing a logical 0, and the electron in the right dot representing a logical 1. Another approach uses a linear array of single-electron quantum dots, and encodes the qubit in the spin of the excess electron [15].

In a third approach, the only operation needed is an exchange between two neighboring qubits, accomplished by lowering the electrical potential and allowing the electrons to tunnel. This is easier to accomplish than precise control of a magnetic field, which would be required in order to affect other gates on specifically addressable bits.

Perhaps the biggest disadvantage of this approach is that exchange-only computation requires encoding a single logical qubit onto multiple physical qubits. A CNOT, for example, requires each logical qubit to be encoded in three physical qubits, and the exchange times must be controlled fairly precisely. TheCNOT on neighboring logical qubits requires 19 exchange operations [DiVincenzo et al. 2000], though Myrgren and Whaley [2003] have found interesting optimizations that allow non-neighbor operations to be effected in 28% fewer total operations than the obvious formulation of repeated use of the 19-exchange CNOT.

Continued compiler work may reduce the encoded execution time penalty further, though the important storage penalty remains.

| **Strengths** | **Weaknesses** |
|---|---|
| Advanced fabrication | Low coherence time |

## III. CONCLUSION

In this paper, quantum hardware implementation methods were considered. The usefulness of the different methods was regarded. According to our survey, the best implementation method was super conducting followed by solution NMR.

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