A Review of SiGe Architectures for Quantum Dot Quantum Computers

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Abstract

In the search for the best architecture of a quantum computer (QC), quantum dots (QDs) have proven to be promising qubits. Using modern techniques in nanofabrication, many variations of QDs have been explored, including materials for their construction, qubit encoding schemes, and measurement techniques. One variation showing exciting progress is silicon and germanium-based spin-encoded QDs, which have demonstrated high coherence times and fidelities, as well as fast qubit control. In this paper we review the following architectures: SiGe planar heterostructures, germanium hut wires, and core-shell nanowires. We discuss the nature of each platform, their advantages and disadvantages in the context of QC, and prospects for scaling.

1. Introduction

Quantum dots are confined semiconductor nanocrystal systems measuring only a few nanometers in size. Spin-based quantum dot quantum computers (QDQCs) have been a topic of great interest to researchers in recent years [1]. By enriching to nearly pure ^{28}Si, decoherence due to nuclear spin is minimized and qubits exhibit long lifetimes [2]. However, by just using silicon there is a tradeoff between the speed of qubit manipulations and coherence time; this dilemma has motivated research of implementing Germanium in QD devices [3]. Holes confined in Ge have spin-orbit interaction energies which are largely tunable, enabling fast qubit control possible. SiGe planar heterostructures, germanium hut wires (HW), and core-shell nanowires (NW) have been extensively researched and much progress has been made with all three. Two families of hole states exist in the bulk of Ge: heavy holes (HHs) of total spin 3/2, and light holes (LHs) of total spin 1/2. HH states have been shown to be most prominent in SiGe quantum wells [4]. Holes have the important feature of effective spins which are strongly correlated with the crystal momentum. The use of heavy hole spins as a qubit encoding is now being implemented by many groups.

In SiGe planar heterostructures, valence band mismatches at each material boundary confine holes within the Ge plane. The strong confinement makes an effective two-dimensional hole

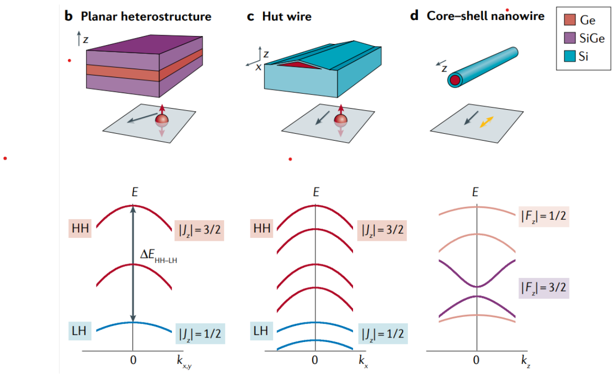

Figure 1: Physical setup and energy band structure of SiGe planar heterostructure, germanium hut wire, and core-shell nanowire [5]

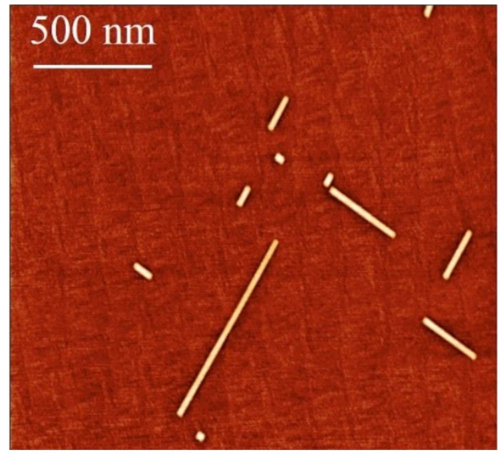

Figure 2: Image of Ge HW grown epitaxially via Stranski-Krastanow mechanism [29]

gas. HHs can propagate in any direction in the plane of their confinement, with their spins pointing parallel or antiparallel to the z axis, as shown in Figure 1b. By modulation doping, holes can be generated in the Ge layer.

Ge HWs have a triangular cross section, and are completely strained in the plane of confinement. Sub-bands in the energy structure occur due to the extra confinement of holes along the x axis as shown in Figure 1c. Like the planar structure, the direction of the HH spin is parallel or antiparallel to the z axis. The mechanism for growing HWs, known as the Stranski-Krastanow mechanism, allows for their well-controlled planar epitaxial growth along a substrate [28]. An example of this is shown in Figure 2.

As in HWs, germanium core-shell NWs are strongly confined along two axes due to material strain (Figure 1d). Unlike the other two structures, cylindrical symmetry present in NWs gives rise to an effective one-dimensional hole gas. By controlling mechanisms responsible for Coulomb blockade oscillations between the Si/Ge layers, gate-defined QDs can be constructed from NWs [6].

2. Comparison of the Structures

A common feature of the three structures mentioned above is that hole spin states present in the Ge bulk are accessible. These hole spin states have a suppressed hyperfine interaction in Ge and, by purifying the bulk material to be nuclear-spin-free, can have very long lifetimes. The spin orbit interaction (SOI) in Ge holes can be tuned to be very strong as well, allowing for fast control of qubit states all-electrically. Unlike conduction electrons, Ge hole spin states are unaffected by valley degeneracy due to their large excited states. These features make Ge hole spin states a viable option for encoding a qubit.

In SiGe planar heterostructures, coherent single and two-qubit control has been demonstrated by N.W. Hendrickx et al. [7]. Using multi-hole modes and exploiting the purity of the SiGe quantum wells, a single qubit fidelity of 99.3% was reported, as well as a CX gate as fast as 75 ns. Quadruple QD 2x2 arrays [8] and a four qubit germanium processor [9] using the planar structure have also been realized. The planar heterostructure has also been shown to yield a T_1 coherence time of 1.2 ms and T_2^* of 0.33 μs by addressing a single hole as a qubit [10]. T_1 and T_2^* coherence times as high as 32 ms [11] and 0.817μs [7] respectively have also been demonstrated. When compared to HWs and NWs, the qubit lifetime in the planar structure is much longer. However, typical Rabi frequencies tend to stay between 30-100 MHz, reflecting that coherence and fidelity come at the expense of speed.

Of the three structures, HWs offer the fastest single-qubit control. By taking advantage of Ge holes' strong spin orbit interaction (SOI) and applying microwave bursts to a HW double dot, an experiment has shown to achieve an ultrafast Rabi frequency of 540 MHz with all-electrical control [12]. This result came with a dephasing time of 84 ns. Recently, this same group achieved a most-impressive Rabi frequency of 1225 GHz with dephasing time of 20 ns, putting HW single-qubit control speed far above that of the other considered platforms [13]. An ultrafast Rabi frequency of 435 MHz has also been demonstrated with core-shell NWs [14]. Remarkably, the one-dimensional nature of NWs allows for great tunability of the so-called Direct Rashba SOI (DRSOI) [15]. This sets NWs apart from the other structures; by tuning this DRSOI, it is possible to switch between regimes of ultrafast control and long coherence times. However, due to a reduction in non-Ising type coupling to nuclear spins, HWs generally have longer coherence times than NWs [16]. Nonetheless, by improving the speed and efficiency of the DRSOI mode-switching technology, NWs seem to provide wider utility than HWs.

3. Scaling

In order to scale, a quantum computing system must be able to prepare, manipulate, and measure qubits with high fidelity. The popular surface code, requiring fidelities no lower than 99%, is an optimal error correcting technique for silicon QDs; their small footprint allows for dense qubit arrays and tiles. A complete universal gate set has now been demonstrated on a two-qubit SiGe heterostructure device with fidelities that satisfy the surface code's requirement [17]. With their gate set, they used the variational quantum eigensolver algorithm to approximate the ground state energy of molecular hydrogen, achieving results with comparable error to what has been seen with trapped-ion qubits [18].

By demonstrating qubit control with fidelities above the threshold for the surface code, the discussion of scaling the number of qubits in the system becomes the next challenge. It has been observed that the manufacturing of QDs is similar in ways to that of field-effect-transistors [19]. This connection may be a gateway to scaling QDs by integrating CMOS technology into the computing system. For this to happen, a plan to reproduce high fidelities across large sets of qubits is essential. Research groups have looked into different plans for just this [20-21].

Gonzalez-Zalba et al. discusses general ideas for scaling a hybrid classical-quantum computing system using silicon QDs and CMOS technology [22]. In their paper, a blueprint of a three-layer quantum computing system is proposed: a quantum layer, a quantum-classical interface, and classical layer. The quantum layer, referred to as the quantum processing unit (QPU), would consist of qubit arrays in geometries needed for implementing the surface code. The classical-quantum interface would be in charge of qubit initialization, manipulation, and readout, as well as routing all signals to and from the QPU. This layer would also communicate information to the classical layer from the surface code's error detection. The classical layer would be in charge of correlating this information with error types, as well as compiling quantum algorithms given by the user into appropriate control and readout steps. Challenges still arise at every layer of this system. For the QPU, it is a challenge to find the optimal geometry for qubits and electronics while adhering to the physical requirements of the surface code. It is also challenging to implement the necessary integrated circuits at cryogenic temperatures. In principle, one can raise the temperature of the QPU at the cost of reducing qubit/gate fidelities, but this is a balance which needs to be treated carefully when discussing large-scale quantum devices. Still, using CMOS technology to some capacity in scaling a silicon QDQC would bring the added benefits of low-cost and compact manufacturing.

A major challenge in scaling QDs is fast readout of qubits with high fidelity. Techniques such as using radiofrequency reflectometry and resonant circuits have been demonstrated, but each have their benefits and drawbacks within the realms of high and low bandwidth limits. In a SiGe planar heterostructure, an on-chip superconducting microwave resonator has been demonstrated to achieve high-bandwidth single-shot readout in 6 μs with a fidelity greater than 98% [23]. It is noted that the qubits measured with this technique had a shorter relaxation time than typically found in silicon dots. Nonetheless, this technique's speed and high fidelity allows for efficient measurement of qubit arrays. Additionally, it can be applied to other types of silicon QD qubits in a magnetic field.

Superconducting microwave resonators also have the useful application of entangling qubits at long distances. A group in Hefei, China, has coupled hole double QDs to a microwave resonator by taking advantage of the strong spin-orbit coupling present in Ge HWs [24]. Since the dimensions of these resonators are much larger than the qubits being entangled, large networks of spin qubits could potentially interact with one resonator in a large-scale QDQC.

4. Conclusion

Included in this section is a venn diagram illustrating the similarities and differences between each platform (Figure 3). In the appendix we have a table compiling fidelities, coherence times, and qubit manipulation speeds achieved with the three platforms in recent years.

In conclusion, QDs offer great variability in their possible structures as qubits. Using Si and Ge to construct them allows for exceptional fidelities, coherence times, and qubit manipulation speeds, albeit not all at once. While SiGe planar heterostructures offer coherent control of qubits with great fidelities, HWs and NWs offer very fast qubit control. NWs seem to offer

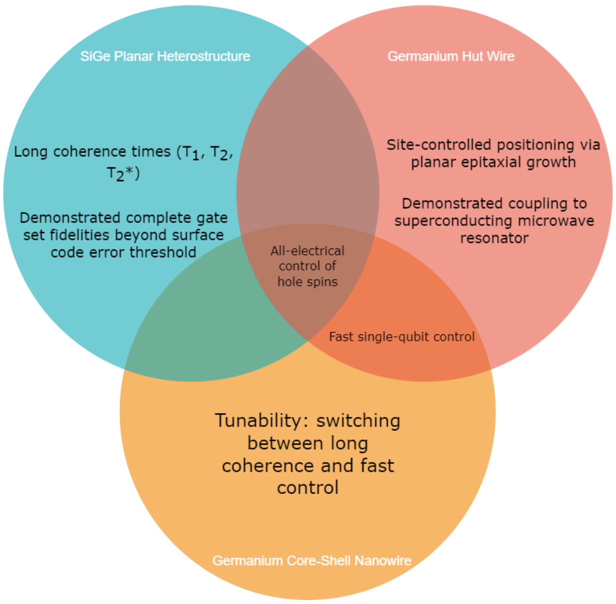

Figure 3: Venn diagram comparing SiGe planar heterostructure, Ge hut wire, and Ge core-shell nanowire

the most versatility as qubits due to the DRSOI tunability. The achieved complete high-fidelity gate set with planar structures is a big step towards scaling dense qubit arrays. Demonstration of ultrafast control and spin-resonator coupling with HW also shows their potential as efficient qubits. All of these structures have the potential to be scaled up, and it will be exciting to see how they improve in the near future.

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Appendix A. Table of Compiled Results

Architecture	Year and reference	Rabi Frequency	T1	T2	T2*	1-Qubit Gate Fidelity	2-Qubit Gate Fidelity	Driven Coherence Time	Measurement Fidelity	Notes
Si/Ge Planar	2015 [25]			28 ms	120 µs					
	2018 [26]	3.93 MHz			24.8 µs	Clifford: 99.861 Average Gate 99.926				Quality factor of 888
	2019 [27]	410 kHz		290 ±40 µs	24.3 ±2 µs	>99.9%	94.7% ±.8%			
	2019 [23]		159 µs						>98%	
	2021 [17]					99.72%	99.5%			Above error threshold of surface code
Ge Hut Wire	2002 [7]	540 MHz								84 ns dephasing time
	2023 [13]	1.2 GHz			21.5 ns					Electrically tunable Rabi frequency
Nanowire	2014 [30]	400 – 830 MHz	800 ns		180 ns- .18 µs					
	2021 [12]	435 MHz						7-59 ns		

Figure A.4: Compiled results of qubit coherence, gate fidelities, and maniuplation speed. Organized by SiGe planar, hut wire, and nanowire strucutres