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Semiconductors a platform for scalable Quantum Computing

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Management Summary

Semiconductors play a crucial role in the information era, and their significance extends to the rapidly evolving field of quantum computing. Over the last decade, semiconductor quantum technologies have emerged as a focal point of global research and developed with remarkable speed. The research varies from initialization, control and readout of qubits, to the architecture of fault tolerant quantum computing. In this paper we first introduce the basic ideas of quantum computing. Subsequently we delve into the challenges that confront the quantum computing landscape and how they can be tackled using semiconductor technologies and already widely used classical electronics technologies. Finally, we address the advantages of spin qubits in semiconductor platforms, emphasizing their scalability and reduced susceptibility to decoherence, the main challenges in quantum computing.

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Introduction: Supercomputers versus quantum computers

Supercomputing	Quantum Computing
Supercomputers rely on classical bits to process information using traditional binary logic. They perform complex calculations by executing sequential instructions in a highly parallelized fashion. While they excel at certain tasks, they face limitations in handling exponentially growing computational demand.	Quantum computing leverages quantum bits (Qubits). They can perform parallel computations on all possible states of the qubits, enabling exponential speedup for specific algorithms. However, they are still in the early stages of development facing severe challenges, such as susceptibility to errors and precise qubit control

Unsolvable problems using classical computers: When scientists encounter difficult problems, they use supercomputers. These are large traditional computers, often with thousands of traditional CPU cores. But also, the best supercomputers struggle to solve a certain type of problem. **If supercomputers get stuck**, it's probably because the complexity of the problem is too high, i.e. a problem with too many variables that interact in complicated ways. Example of these problems can be **modeling the behavior of individual atoms** in a molecule or the determination of ideal routes for several hundred tankers in a global shipping network, tasks Quantum computers can easily solve.
However, quantum computers will not only bring advantage, but also **risk to traditional security technologies** regarding cryptography. One example is the ability to factorize large numbers into their primes, a method used for decades to encrypt and secure data and todays communication. The following example will illustrate the power of quantum computers.

Example: Factorization of large numbers
What are the prime factors of 15? This seems like a very simple question that even a middle school child could answer. However, factoring is surprisingly challenging for classical computers. This forms the basis of many modern encryption algorithms, which use large numbers and their prime factors to secure data. This inefficiency of classical computers drives much of the excitement surrounding quantum computers, since they can factor large numbers much more efficiently using Shor's algorithm. This has not only potential impact on cryptography, but it can provide severe advances in the field of machine learning. A few years ago, a team of researchers became to first to demonstrate this algorithm on real quantum hardware. If a large integer is to be factorized into its primes and the quantum computer requires 30 seconds to solve the problem, the classical computer would roughly require 34 years to solve it. This shows the dimension of the impact of quantum computers, especially in the field of cryptography.
It is important to note, that this is still a theoretical example. The quantum supremacy of Shor's algorithm has been demonstrated theoretically. However, it could only be proven practically using the number 15 due to the still limited number of qubits that is available in quantum computers nowadays. To challenge modern cryptographic systems, many challenges still must be overcome.

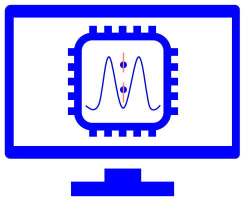
The realization of practical quantum computing, with tangible benefits for real-world problems, necessitates overcoming numerous technological challenges, particularly in addressing hardware limitations. Currently, the quantum computing landscape grapples with a constrained number of qubits, typically ranging from 50 to 100. To unlock the true potential of quantum computing and tackle complex problems that elude traditional supercomputers, a substantial upscale in qubit count is necessary. Estimates suggest that around 1 million qubits may be required to meet the high computational demands posed by various real-world applications[2].Addressing these hardware challenges is pivotal for ushering in an era where quantum computers can make significant contributions to solving complex problems and advancing scientific research.

Sources

1) Shor's Algorithm: Shor's algorithm is a quantum algorithm for finding the prime factors of an integer. It was developed by the American mathematician in 1994. It is an example of superpolynomial speedup compared to the best classical algorithms.
2) Science: IBM promises 1000-qubit quantum computer – a milestone – by 2023

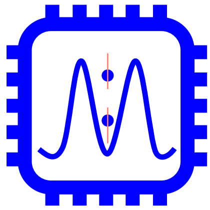
From classical to quantum: A new era of computing

Quantum computer: The quantum computer itself is an electronic device like a classical computer as we know it. It has cables and very complex cooling systems. The cooling is necessary to keep the errors of the quantum computation as low as possible. Depending on the qubit type, temperatures need to be as low as a few millikelvins. The computations are being performed in the core component of the computer, the quantum processing unit which is simply the chip of the computer. It sits at the very bottom of the computer and is the component that is to be cooled and often considered as the computer itself.



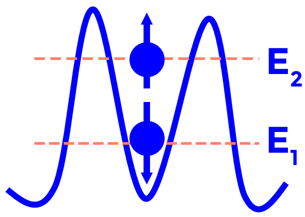
Quantum computer

The quantum processing unit: The quantum processing unit (QPU) is the analogous component to the core processing unit (CPU) in a classical computer. It performs all operations of the computer like the chip as we know it in a classical computer. Since it operates using qubits, it needs to be cooled down to extremely low temperatures and protected from environmental impacts in general to be able to control the sensitive qubits. In the future the QPU will incorporate millions of qubits, making quantum computing more practical.



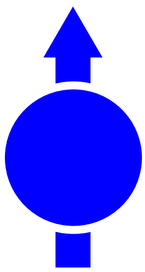
Quantum processing unit

Quantum dots: Quantum dots are nanoscale structures (2–10 nm) usually made of silicon that exhibit properties that differ from those of larger particles due to their quantum mechanical effects. In this context, quantum mechanical effects mean, superposition and entanglement is possible in contrast to macroscopic systems. They can trap individual electrons which can be used to implement the qubit. The needed confinement is created by potential landscapes that are shaped by voltages applied to electrodes. It can be considered as a potential minimum that traps an electron via electric fields. The electron will act as the qubit inside the quantum dot.



Quantum dot

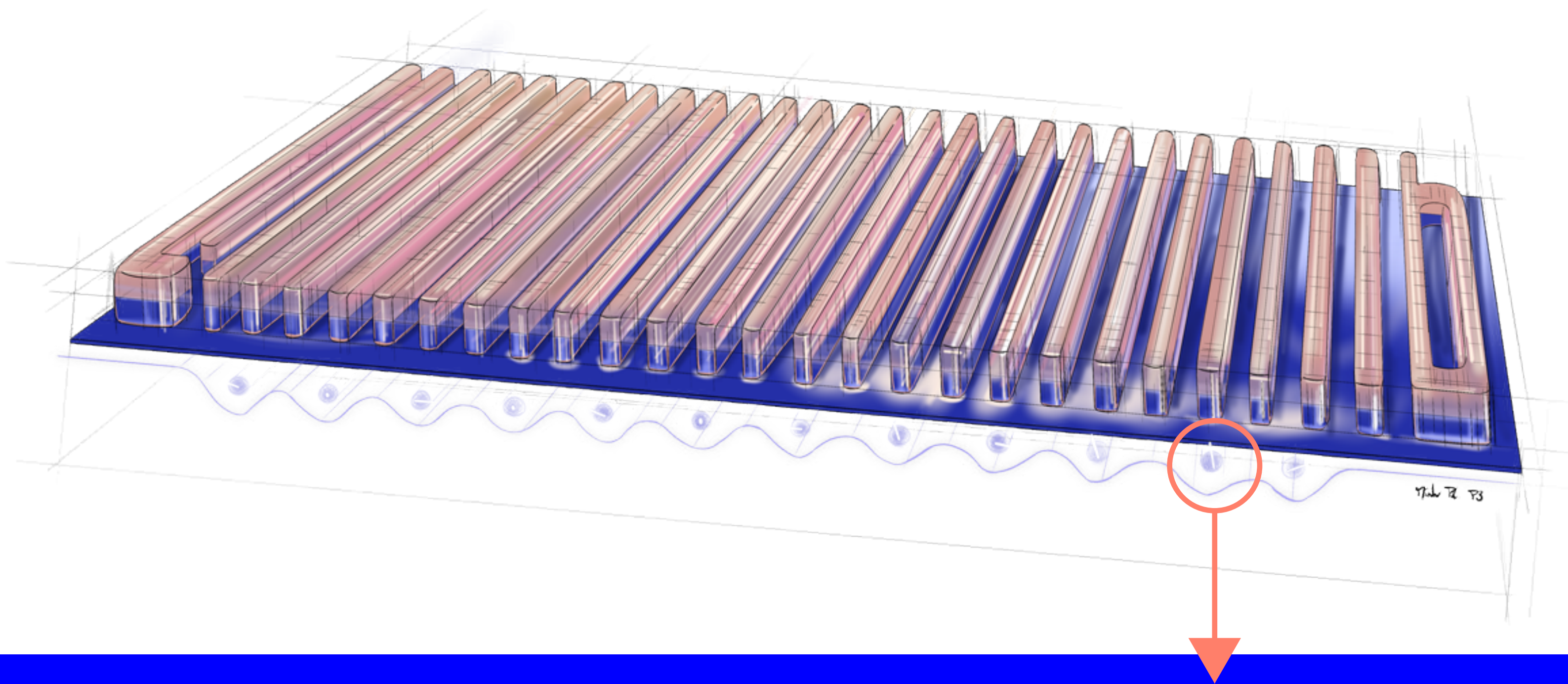
Spin qubits in quantum dots: Inside the quantum dots, we have the quantum bits (qubits). These are the smallest unit of information in a quantum computer like bits in a classical computer. Qubits can be realized in various ways, and it will be shown how semiconductor technology can be advantageous. Qubits are very sensitive to the environment which is why they need to be isolated as good a possible to make fault-tolerant operations. They are the most important part of the quantum computer and the core difference to classical computers which work with bits. In the context of quantum computing, the information is encoded in the spin state of the electron which can occupy two distinct values and can also exist in



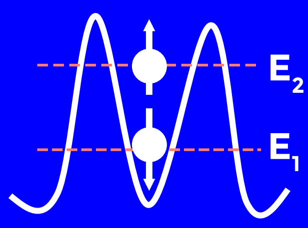
Spin qubit

Quantum hardware:
Semiconductor quantum dots

Semiconductor quantum dots are potential landscapes implemented in silicon or other semiconductor materials. The potential landscapes are created using electrodes fabricated with nanotechnologies. The picture below shows several quantum dots that are all built on a single quantum processing unit. These quantum dots act as potential traps for single electrons and therefore capture them. The spin of these confined electrons can then be used to implement a qubit and perform quantum operations on the chip. Spin qubits in semiconductor quantum dots have severe advantages over other qubit types in terms of general challenges regarding quantum computing that will be discussed during this whitepaper.



The figure above shows a quantum chip with 12 qubits. Each little dip in the line represents a single quantum dot. The quantum dot is an electrical potential, produced with electrodes. Each quantum dot can be considered as an electron in a potential. Inside the dot, the spin of the electron can take up two distinct values, up or down. Due to the laws of quantum mechanics, superposition can occur, and an actual qubit is implemented inside the semiconductor. A magnified version of each quantum dot confining one electron spin qubit is shown in the schematic.



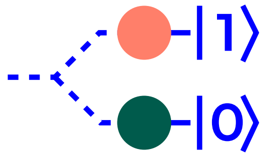
Quantum dot

Sources

3: Intel - Intel's New Chip to Advance Silicon Spin Qubit Research for Quantum

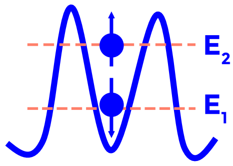
Quantum hardware:
Spin qubits in quantum dots

Qubits are quantum mechanical two-level systems, the simplest but one of the most important models to explain a large variety of phenomena. These systems only have two levels, which are generally represented by the energy states of the system, i.e. E1 and E2. These two energy states can be mapped to the logic states 0 and 1 to represent a bit in classical computers. Additionally, according to the laws of quantum mechanics, these **systems cannot only exist discretely in one of the two energy states but can coexist in an arbitrary superposition of both levels.** Therefore, the states are no longer limited to the two values 0 and 1 and therefore allow to implement qubit i.e. a combination of 0 and 1 simultaneously. There are several ways to implement two-level systems within actual physical systems. These systems can be superconducting qubits, trapped atoms/ions, photonic modes etc. In this whitepaper however, the focus will be on a semiconductor technologies which realizes so-called spin qubits in semiconductors quantum dots.

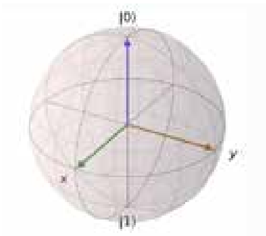


Schematic view: Traditional transistor

Spin Qubits: Spin qubits in semiconductor devices rely on the intrinsic properties of electrons called spin. Spin states can have two distinct values, **"up"** and **"down"**, that can be mapped to the binary values 0 and 1. Spin qubits are manipulated using magnetic fields. They can be implemented in semiconductor quantum dots and provide significant advantages in terms of controlling them as well as scalability.



Quantum Dot



Schematic view of Bloch's Sphere

Another representation of spin qubits inside quantum dot is the so-called Bloch Sphere. The blue arrow on the sphere is the equivalent to the higher energy state E2 or the logic state 1, as shown in the plot above. Using magnetic fields and microwave pulses, it is possible to make that blue arrow move down, making it point towards "1". This would correspond to the lower energy state E1 or the logic state 0. As it is intuitive to see, the arrows on the sphere cannot only point in two distinct directions, but in any direction. This is the result of the quantum mechanical phenomena called superposition. This is what brings severe advantage over classical bits which can only exist in two discrete values , 0 or 1.

Challenges:
The problems of implementing a quantum computer

The theory of information processing has been revolutionized after the discovery of quantum algorithms that have proven to run exponentially faster than their best classical counterparts, and by the invention of quantum error-correction protocols. However, the construction of a computer exploiting quantum – rather than classical – principles represents a major scientific and technological challenge. While qubits must be strongly intercoupled by gates to perform quantum computations, they must at the same time be fully decoupled from the environment. This is difficult because during some phases, such as the write, control and readout phase, information must be exchanged with the environment. This difficulty does not exist for classical bits inside a classical computer as we know it. Further challenges have been summarized by DiVincenzo in 2000 to built a universal fault-tolerant quantum computer. Analogous to classical computers, they include the implementation of logic gates and the ability to initialize and readout qubits. Two further criteria stated by DiVincenzo are the focus of this whitepaper and it will be explained how semiconductors can help to address them.

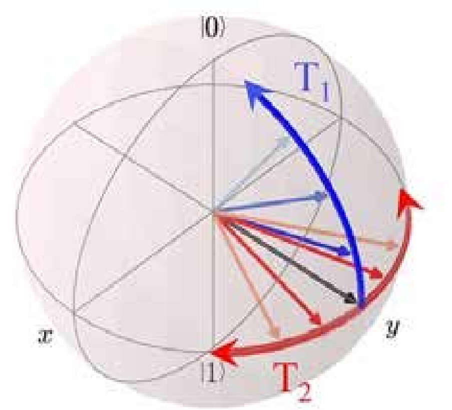
DiVincenzo's criteria (2000): Main challenges in quantum computing that can be addressed particularly well using semiconductor technologies.

1. A scalable physical system with well-characterized qubits
2. Long relevant decoherence times

As mentioned before, it is vital to chose the right system for implementing qubits to address the challenges, namely decoherence and scalability. It has been demonstrated that spin qubits in semiconductors, especially silicon (Si), are a very suitable platform to address those challenges directly and will be discussed in more detail in the following chapter.

Decoherence:
Semiconductors can extend coherence times

To implement a large-scale quantum computer, some experimental challenges must be overcome, especially decoherence. The choice of the system that is being used to implement the qubit is vital for tackling those challenges. It has been demonstrated , that semiconductor devices can be a platform to overcome these natural barriers. Semiconductors can be used to fabricate so-called quantum dots, which provide significant advantage to implement a stable qubit system. In the following the concept of quantum dots, as well as their fabrication process and advantages will be explained.



Schematic view of Bloch's Sphere

Decoherence: Decoherence in quantum physics is the phenomenon of a quantum particle losing its state due to an uncontrolled interaction with external factors like the environment. If the particle was perfectly isolated from the environment it would maintain coherence indefinitely. This definite state is necessary to perform quantum operations on information encoded quantum states. Classical bits do not experience decoherence, which makes computing so much easier.

Decoherence can arise for multiple reasons such as the magnetic fields from the electronics inside the computer or other nearby electronic devices or even more exotic reasons such as cosmic microwave background radiation. Other spins in the semiconductor can also decrease coherence times due to their spin-spin interaction. Spin-spin interaction is one of the most significant source of decoherence and can be addressed very well with semiconductor technology and isotope engineering. Decoherence is visualized on the picture, which shows the black no longer pointing in a certain direction but is "vibrating" and doesn't have a distinct value anymore since it is influenced by the environment, depicted by the red arrows. A follow-up challenge of decoherence is Scalability. The ability of controlling multiple spin qubits individually requires very little decoherence of each one of them.

Scalability is extremely important since it will be necessary to implement around 1 million qubits on a chip and not only 10 – 100 to solve relevant problems using quantum computers.

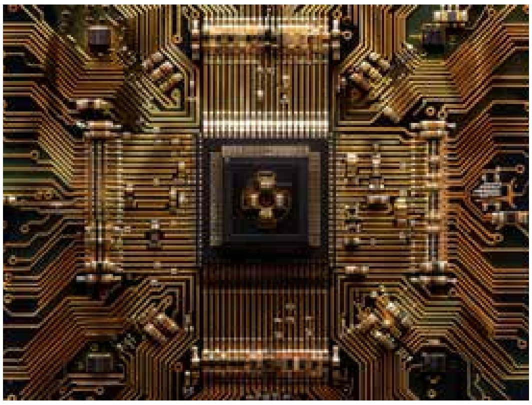
Sources

4: DOI: 10.10387ncomms13575 – A CMOS silicon spin qubit

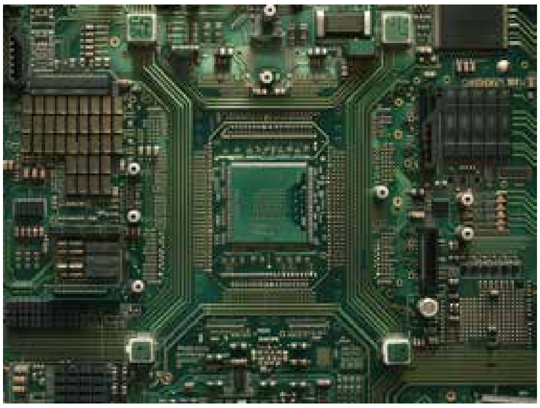
Quantum dots in Semiconductors: Quantum dots used to be implemented in Gallium Arsenide (GaAs) heterostructures. In this material, coherence times were mainly limited by magnetic field fluctuations arising from nuclear spins in Ga isotopes. This resulted in non-negligible spin-spin interaction leading to shorter coherence times. Since **all Ga isotopes have nonzero nuclear spin, it is impossible to eliminate the source** fluctuating hyperfine fields in this material. This limitation has motivated the recent intense effort to implement quantum dots in Si, which has a much lower abundance of nuclear spin isotopes (4.7% in 29Si)4 that can be further suppressed by semiconductor isotope engineering. Furthermore, the problem of electron spins coupling to nuclear spins can be cured largely by means of **spin-echo sequences.** A complex

Scalability:
A CMOS silicon quantum chip

Silicon, the primary constituent of microprocessor chips, is emerging as a highly promising material for the realization of future quantum processors. Utilizing its well-established complementary metal-oxide-semiconductor (CMOS) technology would significantly enhance the development of scalable quantum computing architecture, seamlessly integrating with classical control hardware. The approach involves adapting an existing process flow designed for CMOS transistor fabrication to create devices with qubit functionality. This report, created by Intel, highlights the successful creation of a silicon qubit device using an industry-standard fabrication process, demonstrating qubit functionality within a basic transistor-like structure. This achievement marks a noteworthy stride toward developing scalable spin qubit geometries within a rapidly deployable CMOS platform.



Ai generated depiction of the silicon qubit devices



Ai generated depiction of the silicon qubit devices

The pictures show one of the initial silicon spin qubit devices made available to the research community. Fabricated on 300-millimeter wafers, this 12-qubit3 device harnesses cutting-edge transistor industrial fabrication capabilities, including technologies like extreme ultraviolet lithography (EUV) and advanced gate contact processing techniques. Each qubit device essentially functions as a single-electron transistor, allowing for fabrication using a process like that employed in standard CMOS logic processing lines.
Distinguished by their compatibility with state-of-the-art transistors, silicon spin qubits offer a significant advantage over other qubit technologies. Their compact size, comparable to that of a transistor, is up to one million times smaller than alternative qubit types, measuring approximately 50 nanometers by 50 nanometers[3]. This characteristic holds the promise of efficient scalability, positioning silicon as the platform with the greatest potential for achieving scaled-up quantum computing. Concurrently, the utilization of CMOS fabrication lines enables the application of innovative process control techniques to enhance yield and performance.

Sources

3: Intel - Intel's New Chip to Advance Silicon Spin Qubit Research for Quantum...
Disclaimer: The depictions above were generated by artificial intelligence. they may contain errors or inaccuracies, and should not be relied upon as a substitute for professional advice.

Key Takeaways:

Quantum computers open up avenues for exploring novel problem domains that were previously inaccessible to classical computing, ushering in new frontiers in natural sciences, finance, economics, and various other disciplines.

However, alongside their potential benefits, quantum computers pose a significant threat. The cryptographic systems upon which modern encryption relies will become vulnerable once scalable quantum computers come into existence. Consequently, companies and institutions must proactively prepare to safeguard valuable, long-term data.

The formidable technical challenges involved in constructing scalable quantum computers present uncertainties regarding when these machines will surpass classical computers in computational power and effectively tackle real-world problems. The current strength of quantum computers lies in the order of hundreds of qubits, but significant advancements are required, with qubit numbers reaching into the millions.

Semiconductor materials emerge as a promising solution to address the primary hurdles of quantum computing, particularly decoherence and scalability. Their compatibility with classical CMOS fabrication technology sets them apart from other qubit types, ensuring a unique advantage in terms of integration with classical electronics. This presents an unprecedented opportunity to scale up quantum computers, making them more practical and impactful in the future.

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