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Quantum Computing in Manufacturing

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ABSTRACT

Various industries are becoming increasingly aware of the potential of quantum technology and the prospects for the manufacturing industry are particularly promising.

Quantum computing revolutionizes manufacturing by solving complex optimization beyond classical computers. It enables better routing, dynamic scheduling, energy optimization, and advanced material design by enhancing machine learning and providing deeper insights into complex systems. While quantum computing is still in its early stages, several industries, particularly in manufacturing, are already starting to see its benefits in real-world applications. This paper looks at the potential impact of quantum computing on manufacturing.

KEYWORDS: technology, quantum computing, QC, manufacturing, factory, industry

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INTRODUCTION

Innovation is essential for sustained success in manufacturing. This means looking at new and emerging technologies to determine how they can help boost efficiency and profitability and enable production of new products. Quantum computing (QC) is one of these emerging technologies. While the technology is still in its early stages, major advancements are being made, and some industries, particularly in manufacturing, are already starting to explore its use cases. Quantum computing and machine learning are emerging technologies with the potential to significantly enhance speed, precision, and resource efficiency in the manufacturing industry.

Quantum technology is a field of science and engineering that uses the principles of quantum physics to create devices and applications that have extraordinary capabilities. It is an emerging and exciting area of research and development that has the potential to transform many aspects of our society and economy. Understanding quantum computing requires knowledge of physics, programming, and other high-level fields of focus. The prominent technologies developed by using quantum properties are computing, simulation, sensing, and communication. The shift in the manufacturing environment with emerging technologies is making quantum computing quite truly a disruptive technology in that it has the potential to change the paradigm of production efficiencies [1].

QUANTUM COMPUTERS

A quantum computer (QC) behaves according to the laws of quantum mechanics. Thus, quantum computers are different from binary digital electronic computers based on transistors. A major difference between classical and quantum computing lies in the way they encode data. While a digital computer requires that the data be encoded into binary digits (0 or 1), quantum computers use quantum bits, which can be in superpositions of states [2]. In other words, instead of storing information in bits as conventional digital computers do, quantum computers use quantum bits, or qubits, to encode information. (Qubits are the basic units of quantum information.) In addition to ones and zeros, qubits have a third state called "superposition" that allows them to represent a one or a zero at the same time. Figure 1 shows the comparison between the bit and qubit [3]. The computing power of a QC grows exponentially with the number of qubits it uses.

Quantum computers have the potential to perform certain calculations significantly faster than any digital computers. QC consists of a quantum processor which operates at a very low temperature (a few tens of mK) and an electronic controller which reads out and controls the quantum processors, as shown in Figure 2 [4]. Several forms of physical media (optical fibers and free space) can be used to deliver quantum information. Figure 3 shows a representation of quantum computing [5].

In quantum system, the computational space increases with the size of the system. This enables exponential parallelism which leads to faster quantum algorithms. Unlike classical computer, QC offers massive parallelism within a single piece of hardware.

A typical quantum computer is shown in Figure 4 [6]. The basic building blocks of quantum computers include quantum gates, quantum memories, quantum CPUs, quantum languages, and quantum languages [7,8]:

- *Quantum Gates:* Quantum computers require quantum gates, which are basically different from classical Boolean gates seen in a conventional computer (AND, XOR and so on). A quantum gate acts on superpositions of different basis states of qubits. The quantum gates perform unitary operations on quantum states and lead to quantum circuits. They are particularly important for quantum error correction and experimental quantum information processing. They can be realized by superconductors, linear optic tools, or quantum dots**.** Common quantum gates are CNOT and SWAP.
- *Quantum Memories:* Quantum memories store the quantum systems in a quantum register for information processing. Quantum memories are formulated by n stationary quantum states. Quantum computers are expected to have limited memory.
- *Quantum CPUs:* These use a quantum bus for the communication between the functional elements of a quantum computer. From a computing perspective, quantum CPUs can be approached through quantum adders.
- *Quantum Languages:* These enable us to create an artificial quantum computer to simulate a quantum computing environment. The programming language should follow a functional programming structure, which can compute the process as a whole entity with a proper bounded structure.
- *Quantum Algorithms:* Quantum algorithms are significantly faster than any classical algorithm in solving some problem. Most of the successful quantum algorithms use quantum Fourier transforms in them because they require less hardware. Popular quantum algorithms include Shor's algorithm (since integer factorization is faster) and Grover's search algorithm.

In ambitious attempts to realize practical quantum computers, enormous efforts are still being expended both in designing software (quantum algorithms) and hardware development (physical implementation).

QUANTUM COMPUTING IN MANUFACTURING

Manufacturing is a primary industry that is instrumental to the development of economies of today and in the future. The past few years have highlighted the vulnerabilities of traditional manufacturing and supply chains, from pandemic-driven disruptions to escalating ransomware attacks and climate-induced shocks. To transform manufacturing challenges into advantages, companies should incorporate new technologies—including quantum computing—into their operations now. Quantum computers excel at problems with massive datasets and variables, such as logistics or material simulations, where classical computers falter. They will take the fourth industrial revolution to a whole new level. Manufacturing a quantum computer requires expertise in various fields, including physics, material science, and engineering. Figure 5 shows a representation of manufacturing in quantum computing [1].

Quantum computing's next breakthroughs will come from factories, not physics labs. Today, quantum computers and computing services are available from companies such as IBM, Google, and D-Wave. The companies have identified complex business problems where quantum hybrid solutions can deliver an edge to help drive revenue, streamline operations, and reduce costs. They offer quantum computing services, but using them requires expertise that's hard to come by. Manufacturing workers using quantum computer are shown in Figure 6 [9], while IBM researchers working in a lab are shown in Figure 7 [10].

APPLICATIONS OF QUANTUM COMPUTING IN MANUFACTURING

From optimizing supply chains to discovering new materials, quantum technology offers a range of applications that could radically improve efficiency, lower costs, and spark innovation. Advancing from theory to practice, quantum computing portends progress in sectors such as drug discovery, optimization, data analysis, and forecasting. Key applications of QC in manufacturing include the following [11,12]:

- *Optimization:* One of the significant benefits of quantum technology is in the optimization of your manufacturing operations. You could optimize the manufacturing of individual parts and their impact on the whole system. Quantum computers will have significant implications for industries that rely on optimization to assess various potential outcomes, each with numerous dependencies and constraints. The prospects for hybrid quantum optimization algorithms in the manufacturing industry are particularly promising. Quantum algorithms can optimize complex manufacturing processes, such as machining, welding, or assembly, to minimize defects and maximize efficiency.
- *Material Science:* The creation of new materials is a cornerstone of innovation in the manufacturing and material sciences sector. Traditionally, the process for optimizing existing alloys and developing new ones involves a lot of trial and error, and significant time and expense. Quantum computers could revolutionize materials development and lead to the creation of more efficient and durable manufacturing materials. Quantum technology allows organizations to simulate molecular and material behavior at an atomic level, enabling the development of new materials with desired properties. Already used for drug discovery, quantum computing can help identify new material compositions that will be stronger and lighter than those available today and do so far faster. This is a big boon to industries such as aerospace, automotive, and electronics in material development. The likely first application for quantum computing in the pharmaceutical industry will be to improve computer-assisted drug discovery (CADD).
- *Quantum Chip Manufacturing*: Quantum chips lie at the heart of every quantum computer. Their fabrication demands expertise across physics, materials science, electrical engineering, and nanotechnology. Quantum chip manufacturing is a complex yet fascinating process that sits at the intersection of physics, materials science, and nanotechnology. It is the process of designing, fabricating, and packaging chips that operate on the principles of quantum mechanics. These chips lie at the heart of quantum computers and are responsible for generating and manipulating qubits. Parameters such as coherence time, gate fidelity, crosstalk, and scalability are tested digitally and optimized before physical fabrication begins. Quantum chips are fabricated in cleanrooms using advanced nanofabrication techniques. Due to complexity and sensitivity, many chips fail quality standards. Top quantum computing companies like IBM, Google, Intel, and SpinQ are investing heavily in developing scalable quantum chip manufacturing pipelines. Figure 8 illustrates quantum chip manufacturing [13].
- *Car Design:* Automotive companies are exploring how quantum computing can streamline operations, improve efficiency, enhance safety, and reduce environmental impact. BMW is using quantum computing to accelerate its car design process, allowing for faster development of lighter parts and more efficient vehicles. Hyundai and IonQ are collaborating to develop quantum techniques for 3D object detection in autonomous vehicles. This project aims to improve the computational functionality and efficiency of object recognition, enhancing the safety and performance of Hyundai's autonomous driving systems. Rolls-Royce, a British luxury car manufacturer, has been actively working on quantum computing technology in collaboration with various partners. General Motors (GM), an American multinational automotive manufacturing company, has been involved in quantum technologies through various partnerships and investments.
- *Supply Chains*: Perhaps the greatest place where quantum computing can be applied to manufacturing is supply chain management since it deals with a range of materials, production, and distribution. Supply chains are becoming more complex and need to be agile. Quantum computing makes digital supply changes more agile, with accelerated decision-making and enhanced risk management that helps reduce operational costs and lost sales because of discontinued or out-of-stock products. By enhancing agility, it is expected that quantum technology could eventually transform the supply change completely.
- *Transportation:* Organized transportation systems are crucial to support well-oiled production processes of a manufacturing company. The application of quantum computing in transportation can minimize transportation expenses and time through the best route and time/schedule determination. Since quantum computers can compute several conditions at a time like traffic situation, fuel, and delivery time

quantum, it can determine the best route to transport the products.

BENEFITS

The manufacturing industry stands to benefit from quantum computing in several ways. Quantum computing has the potential to provide manufacturers with safer, more streamlined computational processes. It has the potential to offer unprecedented advantages in speed, security, precision, and complexity over classical technology. In this era of complexity and risk, quantum technologies are emerging as next-generation enablers. Quantum technologies could profoundly impact design, control, and quality assurance. Other benefits include the following [14,15]:

- *Automation:* Quantum algorithms can optimize the movement and operations of robots and automated guided vehicles (AGVs) in a manufacturing plant, improving efficiency and reducing energy consumption. Quantum computers will process data faster, allowing automated systems to react faster to new data or changes to data, which will enable more dynamic and adaptive feedback responses for mission-critical applications.
- *Efficiency*: In the face of increasing supply chain disruption, quantum technologies could offer vital efficiencies. Quantum computing is now poised to drive breakthroughs, offering unprecedented efficiency, accuracy, and resilience that go far beyond the capabilities of classical technologies. Quantum technologies could reshape global manufacturing and supply chains, unlocking new efficiencies and fortifying security. Maximizing efficiency in manufacturing requires optimizing complex, multivariable problems.
- *Complexity:* Developing qubits for quantum computer applications is fraught with complexity. Quantum computing, quantum sensing, and quantum security systems are now poised to drive breakthroughs, offering unprecedented efficiency, accuracy and resilience that go far beyond the capabilities of classical technologies.
- *Predictive Analytics:* By analyzing historical data and predicting future trends with greater accuracy, quantum algorithms can help manufacturers avoid bottlenecks or disruptions in their supply chains.
- *Predictive Maintenance:* Predictive maintenance entails monitoring indicators of machine health for signs of impending failure. The goal is to reduce planned and unplanned downtime by doing just the minimum to keep equipment running at the required rate and quality. Traditional predictive maintenance techniques leverage classical machine learning algorithms that are not good enough to process real-time sensor data. Quantum computing can analyze vast amounts of sensor data from machines and predict when they are likely to fail, reducing downtime and saving on repair costs.
- *Data Security*: As your company becomes more digitized, securing your intellectual property, trade secrets, and customer data becomes increasingly important. Quantum computing has the potential to both enhance and challenge data security practices. For manufacturing and material sciences companies, securing sensitive data related to product designs, proprietary formulas, and business processes is paramount.
- *Quantum Advantage:* The potential of quantum computing to transform the manufacturing and material sciences industry is vast. From speeding up material discovery and optimizing supply chains to enhancing product quality and improving sustainability, quantum technology could unlock a wealth of opportunities that were previously unimaginable. Forward-thinking manufacturing, logistics, and mobility businesses can secure a first-mover advantage today by starting to explore specific problems that can benefit from quantum computing.

CHALLENGES

Although quantum computing will offer significant benefits, this technology faces some challenges. Quantum computing requires highly specialized algorithms and are known to be error prone. One of the biggest challenges in quantum computing is real-time correction of qubit errors. A major concern is the threats that it could potentially bring to the security of IT infrastructure. The quantum solution integration with existing IT frameworks presents a challenge for the technology.

Other challenges include the following [16,17]:

- *High Cost:* There are very expensive price tags attached to quantum computers, not just for development but also for maintenance. A single qubit costs $10,000 or more. To do something useful, the requirement would be for 50 or more qubits (usually 100 & more) and thus, the commercial viability of quantum computers is not expected anytime soon.
- *Sustainability:* Sustainability is becoming a growing concern for many companies, and quantum computing can play a role in improving energy efficiency across the manufacturing

process. All manufacturers are under pressure to limit their carbon footprint. Quantum computing will analyze energy throughout the plant, optimize heating and cooling systems, and improve resource allocation, indicating energy-saving alternatives.

- *Collaboration*: Collaborating with academic partners ensures long term fundamental progress. The commercial promise of QC devices means that research in the field extends beyond the traditional boundaries of university laboratories and into the research centers of global corporations such as Intel and Hitachi, both of which have long-standing collaborations with academic hubs in quantum computing.
- *Decoherence:* Qubits are very fragile and sensitive to noise and interference from their environment, which can cause them to lose their quantum properties and collapse into a definite state. This phenomenon is called qubit decoherence and it limits the quality and duration of quantum computation and communication. To prevent or correct qubit decoherence, various techniques such as error correction codes, fault-tolerant architectures, and physical isolation are required.
- *Scalability:* Another challenge of quantum technology is to scale up the number of qubits and the complexity of quantum operations while maintaining high levels of coherence and fidelity. Scaling up quantum devices to thousands or millions of qubits requires overcoming many engineering and design challenges, such as reducing noise and crosstalk, increasing connectivity and control, and optimizing fabrication and integration.
- *Hardware Development*: Developing high-quality quantum hardware is a major challenge that requires advanced materials science, nanotechnology, engineering, and physics. Manufacturing the qubit (quantum computing's underlying component) is crucial for advancing quantum computer technology. For example, superconducting qubits have fast operation speed but short coherence time. Finding the optimal hardware platform for different quantum applications is an ongoing research topic. The manufacturing of qubits necessitates a delicate equilibrium to meet both robust requirements and the ultimate goal of fault-tolerant quantum computing reality.
- *Software Development:* Quantum software is also much more complex than classical software and requires a different paradigm of programming and algorithm design. However, quantum algorithms are also more difficult to implement, debug, test, and optimize than classical algorithms. Developing user-friendly and efficient quantum software tools, such as programming languages, compilers, libraries, frameworks, and simulators, is a key challenge for making quantum technology accessible and practical.
- *Integration with Classical Systems*: The use of quantum computers shall require integration with classical computers to solve manufacturing problems. When establishing a connection of a quantum system with a classical system, it is necessary to ensure smooth interaction and interoperability.
- *Skilled Workforce:* Quantum computing is a very specific interdisciplinary area and there are not many professionals who have a good understanding of both quantum computing and manufacturing. There is a requirement for training and educational initiatives that could produce a capable workforce to utilize quantum technology in manufacturing processes.

FUTURE OF QUANTUM COMPUTING IN MANUFACTURING

The future of quantum technology is a topic of great interest and excitement for many scientists, engineers, entrepreneurs, and users. This field will progress leaps and bounds in the coming five years due to the amount of funding in research that it has received from government and different industries from chemical to defense. The manufacturing sector is set to benefit from super-fast, super-smart quantum computers. Quantum communication in tandem with quantum cryptography has seen a lot of research funding as it plays in the defense and security space. Quantum technology will create a competitive edge for the early adopters and innovators in the industrial segment. The future is indeed exciting for quantum technology and early adopters will have a marked head start [16]. Figure 9 shows a silicon wafer of future quantum processors [18].

Quantum computers promise to give industry and science a boost when it comes to solving complex tasks in the future. The use of quantum computing in the future entails innovative techniques for many major manufacturing processes, including supply chain optimization, material discovery, predictive maintenance, and production improvement. Trends now show that quantum computing will be more accessible and more practical than in the previous decades. Manufacturers will use quantum processors for specific tasks and keep conventional computing for standard operations. It is no exaggeration to say that quantum computing could usher in the next IT revolution. Government and private sector investments in quantum research are soaring and will continue to soar [1].

CONCLUSION

Quantum computing offers a vast potential to the world, including manufacturing. It is an emerging and exciting area of research and development that has the potential to transform many aspects of our society and economy. Although it is still in its infancy, researchers and business leaders are already exploring the potential role of quantum computing in manufacturing. Manufacturers who want to strengthen their competitive position must stay alert to the potential of new technologies. As a decision-maker or leader in the manufacturing industry, it is crucial to start preparing for the quantum revolution. Those who can master and use quantum technologies will secure significant competitive advantages. The bottom line is that those who have prepared themselves earlier will be able to utilize the quantum advantage sooner.

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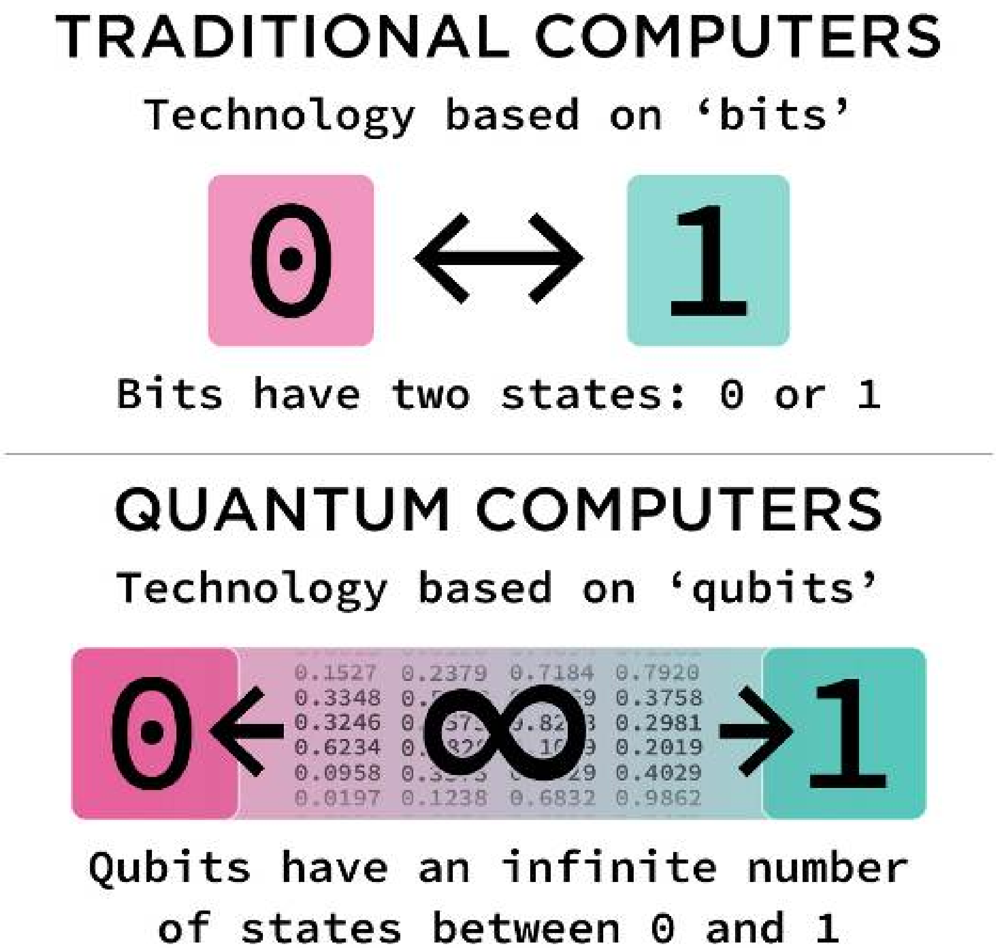

Figure 1 The bit and the qubit [3].

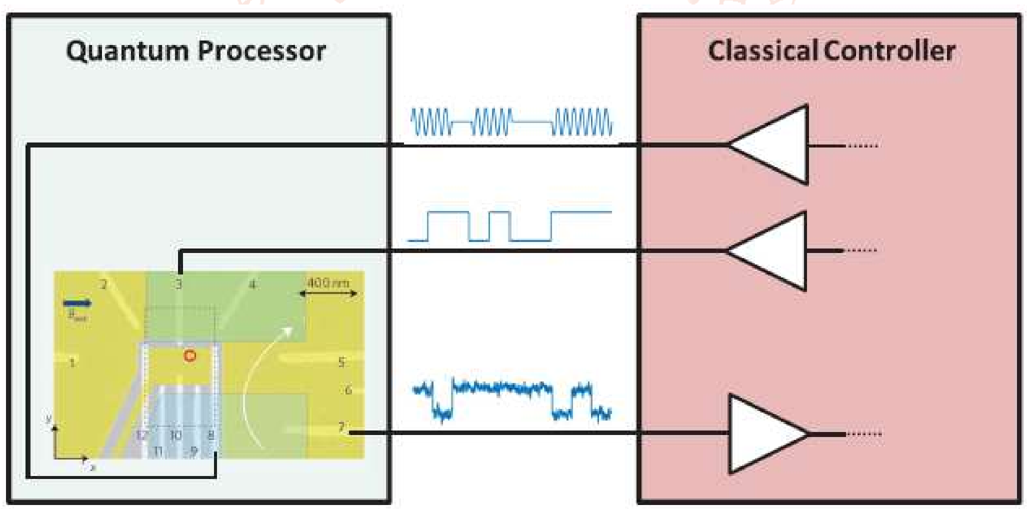

Figure 2 Quantum processor and classical electronic controller [4].

Figure 3 A representation of quantum computing [5].

Figure 4 A typical quantum computer [6].

Figure 5 A representation of manufacturing in quantum computing [1].

Figure 6 Manufacturing workers using quantum computer [9].

Figure 7 IBM researchers working in a lab [10].

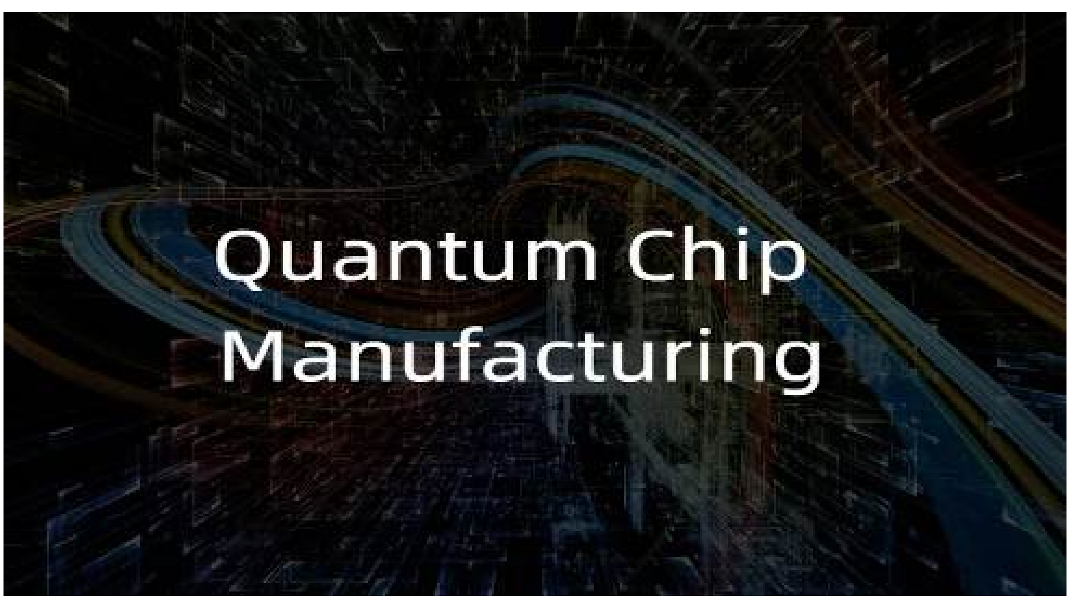

Figure 8 Quantum chip manufacturing [13].

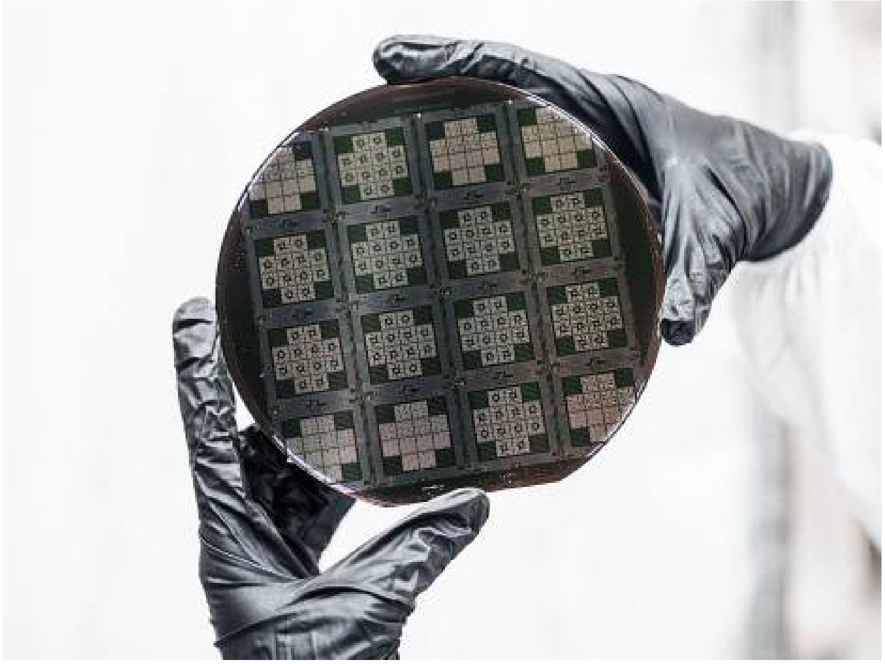

Figure 9 A silicon wafer of future quantum processors [18].