FET Flagships Consultation

Contribution to the Quantum Technologies theme

The Quantum Engineering for Silicon Technology [QuEST] Consortium

The QuEST Consortium covers the supply chain bridging the silicon industry with the quantum technology community. The EU partners of the Consortium signing the documents are:

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Quantum technologies and silicon industry: challenge and vision

The semiconductor annual revenue of Europe has remained substantially unchanged since 2000, while the market has expanded of a factor of two (see **Figure 1 Left**). Such decrease of market share by about a half, despite the increase in demand, can be attributed to a number of factors, including insufficient creation of new actors, insufficient technology transfer from the public research environment to industry and a lack of measures to create a single domain. The size of semiconductor industries in the European Union is comparable to those of Taiwan, just fragmented across many sites.

Novel application of widely studied quantum phenomena such as superposition, quantum parallelism, wavefunction collapse and entanglement could be in principle exploited to radically improve functionalities for several applications, ranging from solving optimization problems such as protein folding, molecular matching, medical applications, stock market simulations, to communication systems, space industry and biological analysis[1].

One of the biggest obstacles to convert successful demonstration of the working principles of quantum phenomena to massively produced industrial applications, beneficial to society, is the lack of an engineered approach to the full stack of technologies and elements required to ensure repeatability, scalability and massive control of quantum effects. **Atomic scale fabrication** of electronic devices is expected to boost advancements beyond as well as alternate to Moore's law. However, there is still a lack of the complete supply chain ranging from the building-blocks such as atoms and electrons, to packaging and control based on standard electronics, physically and robustly realising theoretical models. Such gap prevents the full exploitation of quantum mechanics in high impact information and communication technologies and a boost of the IT market. The challenges facing quantum information technologies are highlighted by:

1) the *lack of investment in engineered methods for atomic scale fabrication*,

2) the *lack of integration with standard semiconductor technology*,

3) the *absence of electronic design for practical quantum control.*

4) the *insufficient robust control methods helping to enable advanced functionalities of complex, realistic quantum devices*

[1] T. D. Ladd et al, Quantum computers, *Nature* 464, 45 (2010)

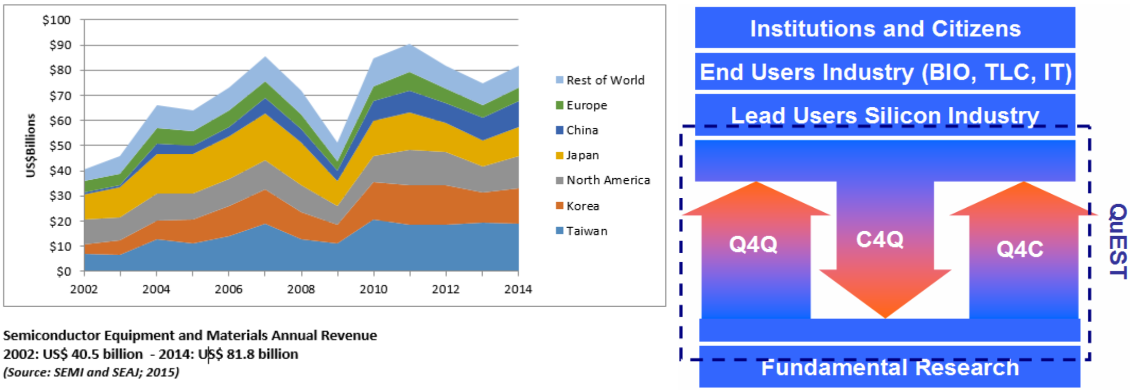

Figure 1 ***Left:*** While the semiconductor market has doubled, Europe maintained the same Annual revenue in the last decade, resulting in a cut of the market share of about 50%. ***Right:*** how QuEST activities fills the gap in the *Value Chain* from fundamental research to society thanks to the pillars of Quantum fabrication technologies for Quantum devices (Q4Q), such as scanning tunnelling microscope method for positioning individual impurity atoms in silicon, Classical nanoelectronics for Quantum control (C4Q) such as cryogenic loop control and FPGA for fault tolerant quantum computing, and Quantum fabrication technologies for Classical digital devices (Q4C) such as single ion implantation and scanning tunnelling method for fabricating single atom based quantum random number generators, single photon detectors and emitters.

The quantum technologies applied to the silicon arena may provide the seed of a new **innovation ecosystem** positioned in the field of silicon technology and focused to generate new knowledge, to activate market opportunities and involve new and high potential actors by offering new technological solutions compatible with existing technology.

The ecosystem obtained by the development of quantum technologies applied to silicon platform provides a hub for semiconductor companies interested to exploit **novel functionalities based on existing materials,** thanks to the added value developed in the quantum technology framework, provided that **all the aspects of the supply chain are covered**. The key point is to exploit existing resources, by renewing the existing supply chain, by extending it to quantum technologies and achieve unprecedented functionalities.

The challenging and innovative target is to exploit the industrially mature silicon platform for developing the full stack of building blocks from theory of quantum control and algorithms, to applied physics of serial atomic scale fabrication methods, to industrial process-compatible silicon control electronics, to serial prototypes for innovative industrial applications.

Such **radically new** fabrication, integration and control methods, relying on atom based silicon technology, will lead to applications such as loop controlled atomic qubit ports, quantum random number generators, and room temperature single-photon emitters and detectors.

Relevance for the European Industry

The proof-of-concept devices and the involvement of **Lead Users** will open the way to promote the establishment of Europe-based quantum computing, quantum ICT and imaging **spinoff companies**. It can also be the basis of future room temperature solutions. Impact will range from security - via new encryption techniques unbreakable by classical computers[2]- to information retrieval among distributed resources of **End Users**. As future perspective, an unprecedented quantum computer can be developed, able to solve **industrial design** problems and human grade **pattern recognition** capabilities among other prospected applications.[3] The quantum communication and imaging solutions developed in silicon may in some cases operate in **ambient temperature**, and thus revolutionize **consumer electronics** as well. One possible application is the analysis and the modelling of complex real-time air or road traffic. The currently expanding healthcare sector can take advantage of such technologies by significantly reducing the time for magnetic resonance imaging (MRI) scans or increase its resolution and chemical specificity to improve, e.g., early diagnosis of cancer or dementia and help to better understand processes in the human body, such as the brain. Finally, the development of cryogenic-to-room temperature standard CMOS silicon technology will have a major impact on **space applications**, where cryogenic temperature and wide temperature variations occur.

[2] J. P. Dowling, "Schrödinger's killer app: race to build the world's first quantum computer" CRC Press, 2013
[3] http://www.dwavesys.com/quantum-computing/applications

Link with international initiatives

Quantum information processing in silicon technology is being heavily funded (100 MEur per year) by Australian Government. Similar initiatives have been adopted also in USA, Singapore and China. Lockheed-Martin, Intel and Microsoft heavily invested in quantum technologies.

What would it take to do it

Scale of the effort required to reach the objectives and how long will it take to do so

Year 1-4: filling the gaps in the supply chain (**Figure 2**) – *Academic groups involved in quantum silicon technology involve new young scientists, PhD and technicians are trained, industries identify most promising methods and routes, collaborations between industries and academy are supported.*

Year 5-6: first lead applications and successful startups – *New generation of quantum engineers of silicon is hired by the industry or create new startups; successful prototypes achieve TRL9; new equipment capable to perform serial fabrication is developed to be integrated with standard silicon processes.*

Year 7-8: industry serially includes specific novel properties by improved processes – *New startups and spinoff companies develop commercial equipment for fabrication of quantum devices to be part of the supply chain, the new fabrication equipment in adopted by silicon industry, the new generation of quantum engineers is active part of the implementation.*

Year 9-10: silicon industry routinely fabricates quantum properties-inclusive consumer devices – *Process methods are smoothed by industry in collaboration with academy, new applications exploiting existing processes are explored.*

The balance of participation and funding gradually shifts from academic institutions to startups and large scale industry. Over time industrial co-funding is expected to increase as the developed technologies get closer to TRL9.

Why is Europe well positioned in terms of skills/expertise and capabilities, including industrial capabilities, to address the challenge and exploit. Research communities to be involved.

Europe has a prominent role in silicon device industrial fabrication with a substantial, large network of small to large companies across different countries. The various steps in device fabrication are represented from wafer manufacturing to integrated circuits with well supported end-product distribution businesses.

Figure 2 Supply chain needed by atom based silicon quantum technology

On the research and development side, Europe has highly qualified human resources with a significantly number of highly ranked Universities, Research centres and research-based industries, which altogether provides a world-class and efficient support for both basic research and product delivery. Many European research groups already work on design, theory, modelling, fabrication and experiments of silicon based quantum devices for both electronic and optical applications and have acquired significant expertise over many decades. Concerning more specifically quantum-based technologies, European scientists are already qualified to enable silicon industry to access such technologies by covering all the layers of the supply chain of silicon quantum devices from theory and design, to serial fabrication of quantum devices, to industrial control electronics, to packaging and validation of the system.

Existing national or European research initiatives linked to this proposal. Added value for such an effort at the European level.

The UK has recently established a quantum technology programme with considerable investment of GBP 270M with GBP 120M invested into Quantum Technology Hubs. The Dutch government, research institute TNO and other organisations have agreed to invest €135m in the development of a quantum computer. CEA in France launched in 2015 a quantum computing on silicon-on-insulator platform initiative.

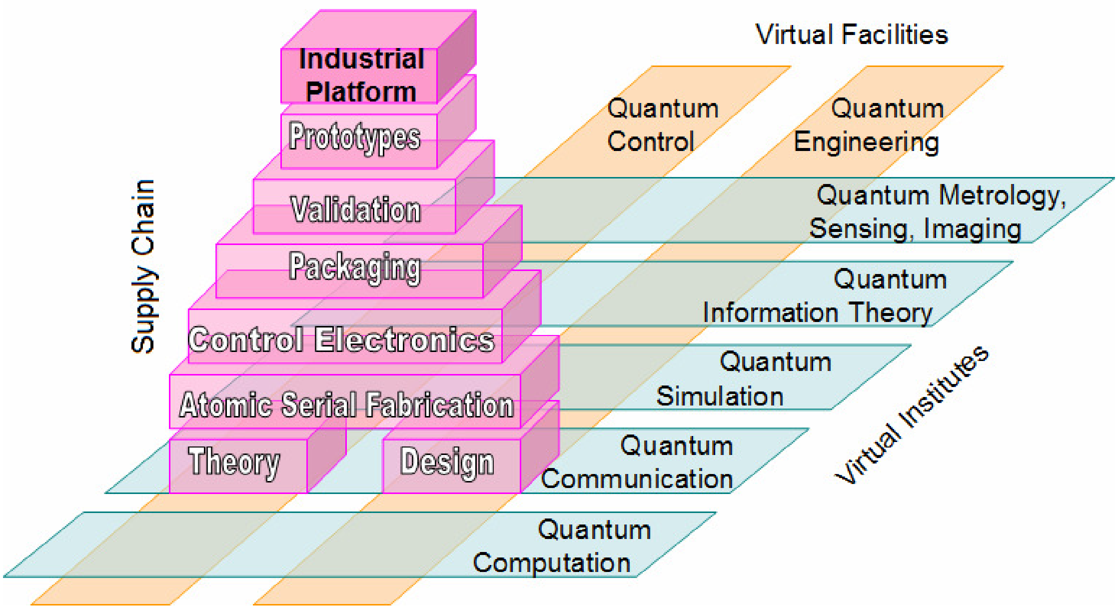

Figure 3 To connect the QUROPE matrix of Virtual Institutes and Virtual Facilities to Industry and Market applications, we propose to introduce a third dimension represented by the Supply Chain connecting the quantum community to mature industrial platforms, such as silicon industry, III-V semiconductors industry, organic materials, silicon carbide, diamond, etc. **In the example above**, the supply chain connects the quantum technologies for quantum communications to an existing industrial platform, like silicon industry. Silicon industry provides the most developed industrial platform and it provides a straightforward test bed for prototyping a variety of quantum technology applications, such as single photon emitters and detectors, quantum processors and sensors. The same model we adopted to cover the silicon supply chain can be exported to other industrial platforms to secure exploitation of other quantum technologies.

EU already invested in the years in quantum technologies, for instance the Coordination and Support Action QUAINT established a quantum control community across Europe, represented as virtual facility in QUROPE - Quantum Information Processing and Communication in Europe. In 2016 the European Commissioner for Digital Economy and Society, G Oettinger, has announced the intention of the European Commission to fund a 1B EUR flagship-like initiative on Quantum Technologies. Currently, the discussion inherent the Quantum Technology Flagship has been based on the vision carried in the years by the QUROPE platform, which arranges the quantum technologies in a matrix of Virtual Institutes (Quantum Computation, Communication, Simulation.. etc) and Virtual Facilities (Quantum Control and Quantum Engineering)[4]. Our vision is to extend such platform along a third dimension (the Supply Chain, **Figure 3**) and to develop quantum engineering in silicon technologies to enable the widest possible utilisation of quantum technologies in all applications to benefit European industry and consequently society. Such model can be extended to other existing platforms such as III-V semiconductors, organic materials, etc. The silicon industry platform may provide the first arena for the development of a complete supply chain from the quantum technologies to industry.

The added value of the European initiative on quantum engineering of silicon technologies consists of

1) the creation of a coordinated and efficient hub to provide novel methods to be transferred to all the silicon industries based in Europe and in new start-up companies;

2) the exploitation of existing silicon European industrial platform by extending its value chain instead of replacing it;

3) the implementation of the synergy between novel silicon technologies and existing silicon technologies, an innovation model to be transferred also to other supply chains for different materials of relevance such as III-V semiconductors, organic media, etc. for which industrial processes already exist.

[4] http://qurope.eu/vs