BAdW BAYERISCHE AKADEMIE DER WISSENSCHAFTEN

WMI

Pressrelease

Nr. 03/2021
29.01.2021

With superconducting qubits on the way to the quantum computer

Building a quantum processor with novel properties based on superconducting qubits - this is the aim of the four year project GeQCoS ('German Quantum Computer based on Superconducting Qubits') funded by the BMBF.

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In this joint project, Germany's leading scientists in the field of superconducting quantum circuits have teamed up to develop innovative concepts for the construction of an improved quantum processor. They aim to realize a quantum processor with improved quality based on new materials and manufacturing methods by the Karlsruhe Institute of Technology (KIT), tailor-made theoretical concepts of the Friedrich-Alexander University Erlangen Nürnberg (FAU), optimized control methods of the Forschungszentrum Jülichs (FZJ) and concepts for new architectures with higher connectivity at the Walther-Meißner-Institute (WMI – Bavarian Academy of Sciences and Technical University of Munich). In order to achieve this goal, semiconductor manufacturer Infineon will develop scalable manufacturing processes, while the Fraunhofer Institute for Applied Solid State Physics (IAF) in Freiburg is promoting the development of optimized chip packages. The processor performance will eventually be demonstrated using a specifically developed quantum algorithm at the WMI.

Improved technology for more powerful quantum computers

Quantum computers hold the promise to efficiently solve problems that are intractable with conventional computers. This includes, for example, the calculation of the properties of complex molecules for the chemical and pharmaceutical industry as well as the solution of optimization tasks, e.g. for manufacturing processes in the automotive industry or for calculations in the financial world. Already today, quantum computers have demonstrated their basic functionality by mastering small, specific problems. The long-term goal of a quantum computer that calculates exponentially faster than a classic computer, however, is still in the future. A suitable architecture for calculating practical problems can only be realized through fundamental improvements in both the hardware and the software.

Within the GeQCoS project, a quantum processor prototype is to be developed that consists of a few superconducting qubits with fundamentally improved components. In this technology the basic building blocks of a quantum computer, the quantum bits or qubits, are implemented by means of currents flowing without resistance in superconducting circuits. These currents are relatively robust to external interference and can retain their quantum properties over relatively long time scales. Together with reliable and scalable manufacturing methods, this has resulted in one of the leading quantum technologies that is already successfully used to build the first quantum processors.

The planned improvements concern, on the one hand, the qubit connectivity, the number of connections between the individual qubits, and the quality of the qubits to enhance the capability to quickly and efficiently produce the desired quantum states. 'By using new types of materials, we expect better reproducibility and a higher quality of the qubits,' says Prof. Ioan Pop (KIT). “We will also improve the manufacturing methods in order to avoid imperfections that effect on the quality of the qubits,” adds Prof. Alexey Ustinov (KIT).

The researchers pay special attention to the interplay between hardware and software, in which they develop algorithms that are ideally matched to the hardware, i.e. the type of qubits and operations as well as the existing connections between the qubits. 'This is the only way to make optimal use of the hardware resources currently available and in the near future,' says Prof. Hartmann (FAU). 'In particular, we will also develop more efficient and precise methods for characterizing the qubits and modeling the overall system,' adds Prof. Wilhelm-Mauch, who recently moved to Forschungszentrum Jülich and is working there with Prof. DiVincenzo and Dr. Bushev on setting up a quantum computing center. Ultimately, however, it is also important to lay the foundations for rapid industrialization and commercialization of quantum technology. This includes a reproducible production of scalable quantum circuits according to industrial standards. 'With its many years of experience in the manufacture of special semiconductor chips, Infineon can make a significant contribution to improving superconducting circuits. To achieve this goal, we can draw also on our quantum technology expertise in the field of ion traps, a second very promising quantum computer platform,' says Sebastian Luber from Infineon. In order to be able to control the highly sensitive quantum circuits accurately and at the same time shield them from the environment, optimized processor housings are being developed in the project. , Scaling to a large number of qubits and operating them at low temperatures also poses great challenges to the packaging technology. Here, however, we can very well adapt the existing tools from traditional fields and apply them to the field of quantum technologies ‘, mentions Sébastien Chartier (IAF).

A nucleus for future quantum computer development

The technologies developed within GeQCoS will not only lead to new scientific knowledge, but also strengthen the quantum ecosystem in Germany and Europe through close links with companies. A specific goal is to make the quantum processor available to first-time users both on the hardware and on the software level as early as possible. Thanks to numerous companies with strong research and development departments, Germany is in an ideal starting position to become a leading center for users and beneficiaries of quantum computing. With access to the processor developed in the project, companies in the quantum technology sector should be strengthened and new start-ups should be promoted.

In addition, the project may serve as the nucleus of the current federal initiative to build a quantum computer 'made in Germany'. The close association between science and industry is a clear commitment to the promotion of technology transfer and to the establishment of a Germany-wide network based on superconducting qubits. The orientation of the project at the interface between engineering, computer science and physics takes into account the interdisciplinary nature of the field of quantum information processing and serves as an important component of the German technology landscape for the training and further education of highly qualified scientists.

This project is also closely related to the **Munich Quantum Valley**, an alliance of the Bavarian ministries, the Bavarian Academy of Sciences, the Fraunhofer Society, the Ludwig Maximilians University of Munich, the Max Planck Society and the Technical University of Munich, which was recently announced by Prime Minister Markus Söder.

'We are on the right track to be able to solve previously unsolvable arithmetic problems with the help of quantum technology. We cannot yet estimate the enormous potential of quantum computers, but there is no question that with this technology we

will be able to gain new scientific knowledge in the long term and also set completely new economic impulses, 'concludes Stefan Filipp, who is as professor at the TU Munich and director at the WMI coordinating the project.

GeQCoS „German Quantum Computer based on Superconducting Qubits“

Funded by the German Federal Ministry of Education and Research
Funding program quantum technologies - from basic research to market
Contract number: 13N15680

The **Walther Meißner Institute (WMI)** of the Bavarian Academy of Sciences has been doing pioneering work in the field of quantum sciences and quantum technologies (QWT) with superconducting circuits in close collaboration with the **Technical University of Munich** for almost 20 years and is involved in a large number of quantum initiatives in the Munich area in a leading role.

Forschungszentrum Jülich (FZJ) addresses quantum computing in quantum materials, quantum computing devices and with the quantum computing user facility JUNIQ. It covers both fundamental research and applications in quantum computing. It also hosts the central laboratory of the European flagship project OpenSuperQ.

At the **Karlsruhe Institute of Technology (KIT),** experimental pioneering work on multiplexed qubit readout, two-level defects, quantum simulators and quantum metamaterials has been carried out and the development of quantum circuits has been advanced.

The **University of Erlangen Nuremberg (FAU)** is one of the most innovative universities in the world. In the group of Prof. Hartmann, besides the development of coupling circuits and qubits, the development of algorithms for near-tearm quantum computers is advanced.

Infineon Technologies AG is a leading global provider of semiconductor solutions with one of the broadest product portfolios in the industry. The company has a high level of expertise in the conception, design and manufacturing of special technologies and is involved in several consortia on quantum technologies, including PIEDMONS on ion trap-based and QUASAR on silicon-based quantum computers.

The **Fraunhofer Institute for Applied Solid State Physics IAF** offers the entire value chain in the field of III/V semiconductors and has many years of experience in the realization of microwave and submillimeter wave modules both in waveguides and on printed circuit boards. In the field of quantum computing, Fraunhofer IAF participates, for example, in the EU project "SEQUENCE" (development of cryogenic electronics) and coordinates the Competence Center Quantum Computing Baden-Württemberg.

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