Quantum Computing Looking Forward

by Chao-Sung Lai and Shao-Ku Kao


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PROF. CHING-RAY CHANG RECEIVED his B.S. degree in physics from National Taiwan University (NTU), Taipei, Taiwan, in 1979, and his Ph.D. degree in physics from the University of California, San Diego, in 1988. Since 1989, he has been with NTU and has had the chance to serve as the executive vice president and interim president of the university. Prof. Chang has worked in micromagnetic numerical modeling since 1980. He not only carried out pioneering studies of micromagnetic structures but also applied the Landau-Lifschitz equation to subnanosecond analysis. Prof. Chang has made significant scientific contributions and has had a great impact on the understanding of nucleation, spin dynamics, and thermal activation of magnetic materials as well as spin transport in low-dimensional materials. He served as the president of both the Taiwanese Physical Society and the Taiwan Associations of Magnetic Technologies. He is a Fellow of IEEE and of the IEEE Antennas and Propagation Society. He was a committee member of the IEEE Magnetic Society and chair of the Taipei Chapter. He served as the general chair of IEEE InterMag 2011 in Taipei. He has authored more than 280 papers and has held more than 28 magnetic-related patents. He was awarded the IEEE Nanotechnology Best Paper Award in 2019. Currently, he serves as the director of the NTU-IBM Quantum Computer Hub and as the chair of the Quantum Computer Promotion Office, Ministry of Science and Technology, Taiwan. Prof. Chang was the founder and served as the president of the Taiwan Association of Quantum Computer and Information Technologies.

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Prof. Ching-Ray Chang.

We at *IEEE Nanotechnoligy Magazine* are very pleased to have the opportunity to invite Prof. Ching-Ray Chang to share his vision on the current status of quantum computing and its potential applications. This interview addresses critical impacts of quantum computing. In addition, some examples of focused research topics of quantum computing in Taiwan are described.

***IEEE Nanotechnology Magazine*:** Can you elaborate on quantum mechanics?

Ching-Ray Chang: Quantum mechanics is one very useful theory in physics. It has deeply changed human life as it is. When the scale of a system is narrowed down to the atomic level, the operation is governed by quantum mechanics. The behavior is the opposite of what you think according to the classical world. The important concepts in quantum mechanics include quantization, superposition, and the entanglement of different quantum states. Quantization deals with the discreteness of a physical quantity. Superposition and entanglement refer to a situation in which quantum states are very different from the classical states.

***IEEE Nanotechnology Magazine*:** What is the current status of quantum computers around the world?

Chang: A universal quantum computer aims to use gate operators to solve problems within a reasonable time, but it needs millions of logical qubits and is unlikely to be mature within a decade. International companies manufacturing universal quantum computers include IBM, Google, Microsoft, NEC, Fujitsu, and quite a few other companies in China. Since the currently available qubits are not enough to achieve a fault-tolerant quantum computer, the noisy intermediate-scale quantum computer has been adopted for special applications in noisy environments with a limited number of qubits.

***IEEE Nanotechnology Magazine*:** Can you talk about the current status of hardware development in quantum computers?

Chang: Quantum computing is based on atoms and light, and the computation relies on the interaction between them. The atom, which forms the storage unit called *qubit*, can be either a real or artificial atom—as long as it possesses two discrete energy levels to couple with light. In systems that require a laser to control the qubits, trapped ions and diamond vacancies are the two major candidates that have been intensely studied in recent years. For solid-state systems, superconducting qubits and spin qubits in quantum dots are two very promising platforms. Superconducting qubits consist of an Al/Al_2O_3-based Josephson junction as an inductor and a shunted capacitor, which equivalently forms a quantum *LC* resonator with discrete energy levels. The qubit is capacitively

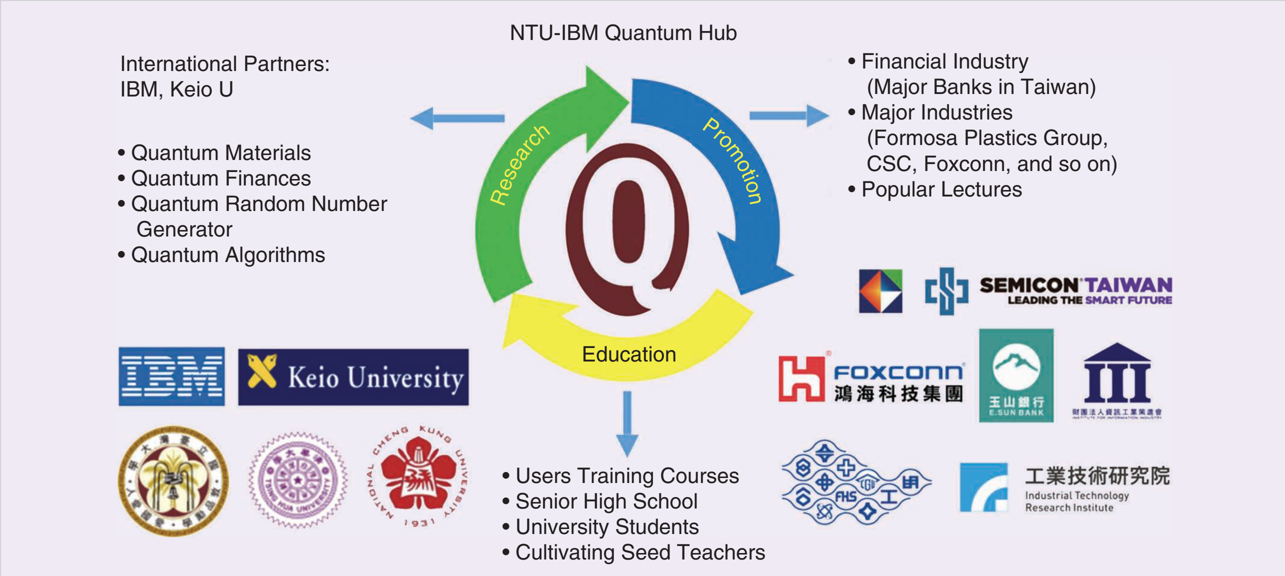

FIGURE 1 The missions for the NTU-IBM Quantum Hub: research, promotion, and education. CSC: China Steel Corporation.

coupled with a superconducting coplanar waveguide whose role is to be a microwave cavity to store the microwave photons and interact with the qubit. Control of the qubit is achieved by applying microwave and dc bias; the former couples to the qubit levels while the latter generates magnetic flux threading of the loop of the superconducting quantum interference device to change the qubit energy. The coherence time of such a system can exceed 100 ms, with a gate operation as fast as 40 ns.

***IEEE Nanotechnology Magazine*:** In what areas can we expect quantum computing to be of practical use?

Chang: The early idea of quantum computing, as suggested by Prof. Richard P. Feynman, was to solve quantum problems. The current technologies for quantum computers are limited. Therefore, the immediate applications will mostly be focused on special-purpose topics rather than on general algorithms suitable to create a fault-tolerant universal quantum computer. The current applications of quantum computing in finance focus on three areas: stock market predictions, portfolio optimization, and fraud detection. These applications can include machine learning (ML), which is one active area in the advancement of artificial intelligence (AI). A number of ML algorithms have been successfully developed. The key focuses in the applications of quantum computing in ML are the increased speed of existing classical algorithms and the exploration of new algorithms dedicated to quantum computing. In chemistry, a common task in calculating the wave functions is to directly calculate the ground-state energy. This provides plenty of room for possibilities in chemistry-related disciplines, such as pharmacy and material sciences. For each phase of technological development, there will exist associated applications for various commercial fields. The new capabilities in each development stage are limited. Applications can progress in the future.

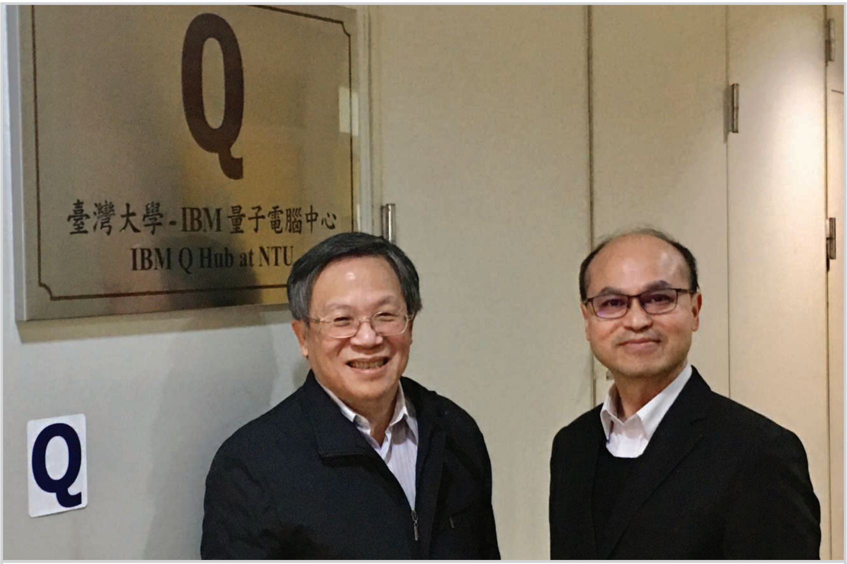

FIGURE 2 (From left) Prof. Chang, director at the IBM Quantum Hub in NTU, and Prof./Dean Chao-Sung Lai, senior editor of the "Highlights" column in *IEEE Nanotechnology Magazine*, standing in front of the IBM Quantum Hub office.

***IEEE Nanotechnology Magazine*:** When did NTU establish the IBM Quantum Hub? What features are available at it?

Chang: In January 2019, NTU announced the launch of the IBM Quantum Hub (Figure 1). At the beginning, NTU researchers could access the IBM Q 20-qubit quantum computing system. Now, the system has been upgraded to the 65-qubit, most-advanced online quantum computer. I am in charge of the IBM

Quantum Hub at NTU (Figure 2). The Quantum Hub serves to provide fundamental research and to promote the applications of quantum computing to major companies and financial institutions. Quantum physics education for high school and university students is also emphasized to prepare the young generations for quantum computing. Key research areas at IBM Quantum Hub at NTU include quantum materials, quantum finances, quantum random number generators, and the use of quantum algorithms. The most important goals of the NTU Hub are to promote research and nurture experts in this novel field as well as to cultivate and educate students for the quantum computing era.

***IEEE Nanotechnology Magazine*:** Please elaborate on the key mission for IBM Quantum Hub at NTU in further detail.

Chang: During the past few years, several developed countries have heavily invested to develop quantum computers. In Taiwan, we still focus on the academic aspect (Figure 3). Multidisciplinary integration is necessary to catch up with global technology trends. Our mission is to establish a strong research team through nurturing quantum computing talents by seeking international cooperation to reach local quantum technology establishments.

Our long-term planning includes:

1) a locally made quantum computer
2) the cultivation of quantum computing talents
3) active international cooperation
4) information and communications technology industrial transformation and upgrading.

***IEEE Nanotechnology Magazine*:** Could you discuss the current hardware research of quantum computing in Taiwan?

Chang: There have been many important research works based in Taiwan related to the hardware of quantum computing (Figure 4). Prof. Ying-Cheng Chen's group reported on quantum memories and achieved a storage efficiency of 92% with quantum optical methods in 2018. Prof. Chin-Sung Chuu's group works on quantum photonics and built the optical fiber link between National Tsing Hua University and National Chiao-Tung University to demonstrate the first outdoor quantum key distribution in Taiwan. Prof. Io Chun Hoi studies the amplification of optical couples with a superconducting qubit. Prof. Yueh-Nan Chen's group studies the measurement of quantum steering and its geometric quantification and observes quantum behaviors. Prof. Ite A. Yu's group works on quantum optics and quantum information and determines the most-efficient cross-phase modulation achieved at low-light intensities without requiring cavities or tightly focusing laser beams. At NTU, there are studies on Si-based qubits and spintronic and quantum devices as well as on quantum computing in ML and AI

FIGURE 3 The first Quantum Hackathon contest at the Xitou resort in Taiwan. More than 60 students worked hard for three days to finish the assigned problems using online quantum computers.

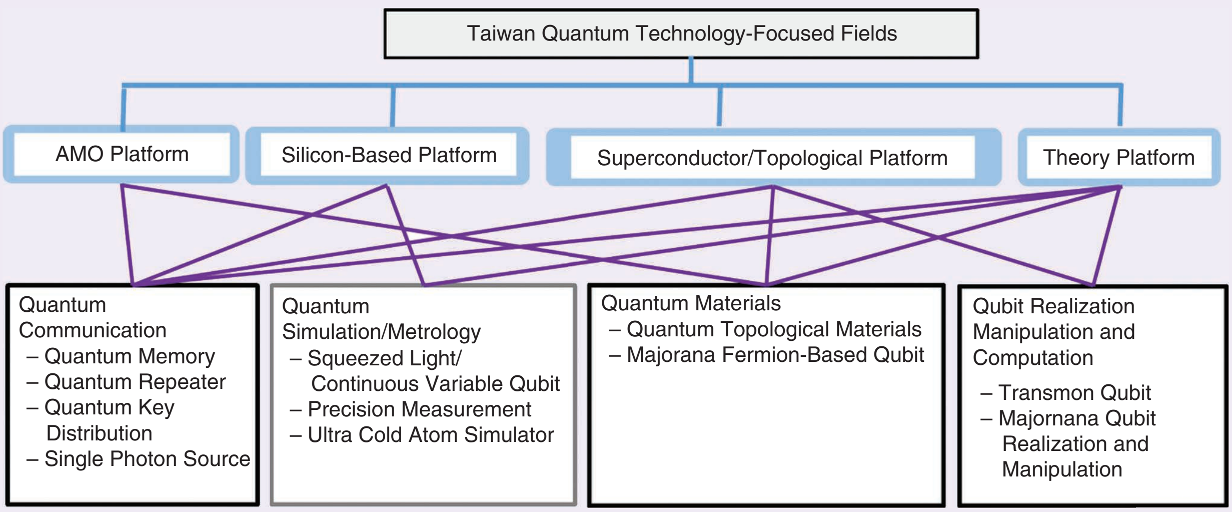

FIGURE 4 The research focuses in quantum technology in Taiwan. AMO: atomic, molecular, and optical.

FIGURE 5 The kickoff day ceremony for HonHai Research Institute. Terry Kuo (founder of HonHai) and Young Liu (chair of HonHai) attended. On the left is Prof. Chang, who serves as the consultant to the institute.

fields. Moreover, Chung Yuan Christian University has proposed to form a College of Quantum Computation to focus on quantum algorithms and applications in industry. At Chang Gung University, a research team has been formed to advance quantum-inspired machines, both in fabrication and in applications.

The semiconductor industry in Taiwan has excellent infrastructure with many talented engineers. Thus, the local industry is very interested in involving it in the development of quantum computers, particularly in the cryogenics peripherals system and quantum-inspired machines. For example, Formosa Plastics Company has a strong interest in the use of quantum computing in material studies and energy applications. HonHai Technology Group and Quanta Computer show great interest in the related researches. In fact, HonHai already established a Quantum Computation Institute under the HonHai Research Institute (Figure 5). To consolidate the R&D resources, including both talents and instruments, the Taiwan Association for Quantum Computer and Information Technology was formed and held its first annual meeting in 2020 December.

***IEEE Nanotechnology Magazine*:** What will the new development strategy for quantum computers be?

Chang: It is important to develop a fault-tolerant logical qubit system with reasonable coherent time. A convenient quantum compiler needs to be developed for daily use for the quantum computers to be used in commercial applications. The core of a quantum computer is the qubit chips (quchips), which can be called *QPU*. The core is similar to the CPU in a modern digital computer. In the use of quantum computers, manipulation of the quantum states is important. The circuit quantum electrodynamics and quantum channels provide a good means of communication between classical and quantum computers. The quantum algorithms operate on quantum computers to calculate or simulate problems that modern computers would need a very long time to execute.

REFERENCES

[1] C. R. Chang, Y. C. Lin, K. L. Chiu, and T. W. Huang, "The second quantum revolution with quantum computers," *AAPPS Bull.*, vol. 30, no. 1, pp. 9–22, 2020. doi: 10.22661/AAPPS-BL.2020.30.1.09.

[2] W.-J. Huang, W.-C. Chien, C.-H. Cho, C.-C. Huang, T.-W. Huang, and C.-R. Chang, "Mermin's inequalities of multiple qubits with orthogonal measurements on IBM Q 53-qubit system," *Quantum Eng.*, vol. 2, no. 2, p. e45, 2020. doi: 10.1002/que2.45.