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In this interview, conducted at the National Institute of Advanced Industrial Science and Technology (AIST), Takahiro Mori Ph.D. provided insights into his research on silicon quantum bit-type quantum computers and integration technology.

Brief History

2001 : Graduated from the Department of Applied Physics, Faculty of Engineering, Tohoku University.

2006 : Received a Doctor of Engineering degree in applied physics from Tohoku University.

2006 – 2009 : Researcher at the RIKEN.

2009 – Present : Researcher at the National Institute of Advanced Industrial Science and Technology (AIST).
Leads the Exploratory Silicon Device Research Team at AIST's Semiconductor Frontier Research Center, focusing on the research and development of semiconductor quantum technology and advanced logic device technology.

> **"Combining my knowledge of integration techniques from transistor research with my prior experience in quantum devices, I shifted my research focus to silicon qubits, leading me to my current endeavors."**

▶ Please introduce your current research.

My current research focuses on the development and integration of silicon spin quantum bit (qubit) technology for quantum computing. Quantum computers represent a revolutionary approach to computation, operating on principles fundamentally different from those of classical computers. At the core of these machines are qubits, which can be realized through various methods, each with unique properties. Current commercial quantum computers utilize technologies like superconductivity, cold atoms, and ion traps, all relying on distinct physical phenomena.

My research specifically explores silicon spin qubits. Silicon, the foundational material for transistors in classical computing, offers significant advantages for qubit implementation. Its compatibility with existing semiconductor fabrication processes holds the potential for large-scale quantum computer development. While alternative approaches, such as those using photons, exist, the optimal qubit technology remains an open question. Ongoing research and development continue to evaluate the strengths and weaknesses of each method.

▶ Please tell us how you started your research and how you got to where you are today.

My journey into quantum computing began approximately 20 years ago during my postdoctoral research at RIKEN. While there, I was introduced to quantum devices and became intrigued by their potential. Following my time at RIKEN, I transitioned to the National Institute of Advanced Industrial Science and Technology (AIST), where I focused on semiconductor transistor research. In 2014, I rekindled my interest in quantum devices, collaborating with a former RIKEN colleague on a small-scale project. This marked the start of my dedicated research in this field. As the field of quantum computing advanced, my involvement grew, culminating in my participation in a major quantum device project in 2018. Since then, I have concentrated my efforts on the research and development of quantum devices.

My academic background is rooted in materials science. However, during my doctoral studies, I became fascinated by the future of computing and the potential of quantum computation. Witnessing the rapid evolution of IT and the rise of the information age, I was convinced that computational progress was inexorable and was curious about what lay beyond the horizon of conventional computing. My exploration of this question led me to quantum computing and to RIKEN. At the time, quantum computing was in its infancy, and practical applications seemed distant. Therefore, I initially pursued research on traditional transistors, but I maintained a latent interest in quantum computing. Years later, with renewed momentum in quantum computing research and the increasing importance of silicon qubits, I recognized an opportunity to leverage my expertise. Combining my knowledge of integration techniques from transistor research with my prior experience in quantum devices, I shifted my research focus to silicon qubits, leading me to my current endeavors.

The Guidance of My Mentor

The words of my mentor, Professor Takafumi Yao, played a pivotal role in shaping my career path. As I neared graduation, uncertain about my future direction, I sought Professor Yao's guidance. He remarked, "If I were your age, I wouldn't be doing the same things; I would pursue something new." His advice emphasized the importance of not only focusing on current technologies but also looking towards the future and embracing innovation. These words resonated deeply, inspiring me to embark on a journey into quantum computing research.

Recently, I had the opportunity to reconnect with Professor Yao, who, with a chuckle, questioned his recollection of offering such advice. Nevertheless, his words had a profound impact on me, serving as a guiding principle throughout my research career.

▶ What are the future prospects for your research?

Numerous challenges remain in realizing practical quantum computers. Current superconducting technologies have only achieved the integration of approximately 1,000 qubits. However, the field aims to reach 1 million qubits, a goal that presents significant technical hurdles and will require substantial time and effort. Despite these challenges, continued faith in the future of quantum computing and persistent research and development are essential. Our research team is dedicated to establishing the foundational technologies that will enable the realization of 1 million qubits, ultimately leading to the development of quantum computers accessible to all. As researchers, we are driven by the profound satisfaction of contributing to society through our work.

The advent of new computing technologies has always inspired dreams and hopes for humanity. Computers form the bedrock of human technological progress; advancement without them would be inconceivable. From the abacus to today's supercomputers, increasing computational power has consistently fueled technological innovation. Quantum computers, operating on fundamentally different principles than classical computers, represent a truly groundbreaking technology. It is a privilege and a responsibility to contribute to this transformative field.

High-Temperature Operation of Silicon Qubits

The high-temperature operation of silicon qubits is crucial for miniaturizing quantum computers and represents a significant research focus. Currently, quantum computers require cooling to extremely low temperatures in the millikelvin (mK) range[1], necessitating the use of large dilution refrigerators. Enabling qubits to operate at higher temperatures offers the potential for miniaturizing these refrigerators, thereby significantly expanding the applicability of quantum computers.

While the term "high temperature" might be misleading in this context, it refers to an increase from the mK range to a few Kelvins. This seemingly small change offers considerable advantages, including the miniaturization of refrigerators and greater flexibility in the placement of control circuitry, ultimately facilitating future integration efforts. Superconducting qubits face challenges in achieving high-temperature operation, making silicon qubits uniquely suited for this advancement. These "hot qubits," as they are known, are garnering significant attention. Developing high-temperature silicon qubits presents a formidable technical challenge, but it is a critical research and development objective in the pursuit of miniaturized quantum computers.

Mitigating Variability for Enhanced Quantum Computer Integration

The realization of practical quantum computers hinges on the successful integration of a large number of qubits. Integration, in this context, entails not merely packing qubits together but ensuring their simultaneous and accurate operation. Consider a modern smartphone, which contains over a billion transistors. The smartphone's diverse functionalities rely on the precise operation of each of these transistors. Similarly, quantum computers require the coordinated and accurate operation of over a million qubits. Therefore, minimizing "variability" among individual qubits and ensuring uniform quality is paramount.

Variability refers to deviations in the characteristics of individual qubits from their design specifications, impacting their performance. Excessive variability can hinder proper qubit function and degrade the overall performance of the quantum computer. In our research and development of integration technologies, we prioritize the mitigation of variability. By developing techniques to control and minimize this variability, we aim to pave the way for the realization of high-performance quantum computers.

> **"Minimizing "variability" among individual qubits and ensuring uniform quality is paramount."**

▶ Could you please share your thoughts on using Samco systems?

I have utilized Samco's equipment for nearly two decades and have consistently found it to be user-friendly. While direct comparisons with other equipment may be challenging, the exceptional stability and reliability of Samco's processes are key advantages. Three years ago, when establishing the clean room for the Communal Fabrication Line for Outstanding Modern Devices (COLOMODE), we integrated four Samco devices into our facility. Reliable equipment is indispensable for research, and Samco's devices have become essential partners in our work.

The four Samco systems located within the COLOMODE clean room, AIST.

Specifically, we utilize two PD-2201LC plasma enhanced CVD systems and one each of the RIE-400iPC and RIE-230LC etching systems. The CVD systems deposit insulating films, such as nitride and oxide films, as well as polysilicon for gate electrodes. The etching systems include both inductively coupled plasma (ICP) and capacitively coupled plasma (CCP) reactors. The ICP etching system is primarily used for etching thin films of insulating materials and semiconductors, including gate metal. The CCP-RIE system is dedicated to metal etching during the wiring process.

▶ What do you keep in mind in your daily research?

Safety is the top concern in our research environment. Our experiments involve handling hazardous materials, including gases and high-pressure gases, demanding meticulous attention to safety protocols.

Beyond ensuring physical safety, we prioritize cultivating a sense of "room to breathe" within our team. We believe that fostering a relaxed and unpressured atmosphere is essential for generating innovative ideas and conducting high-quality research. When researchers are constantly pressured by deadlines and project demands, creative thinking is stifled. Research, at its core, involves exploring new ideas with a sense of

freedom and openness, ultimately leading to the creation of a better future. As a manager, I strive to create an environment where every team member feels comfortable and empowered to pursue their research without undue pressure. I am convinced that an environment that fosters free thinking and exploration yields the most significant and impactful results.

▶ Could you please share your motto?

I especially like the saying of Takeda Shingen[2], "People are the castle, people are the stone wall, people are the moat."[3] As a manager responsible for leading a team, these words resonate deeply with me. Research is ultimately conducted by people. While the abilities of the researchers are important, they are not sufficient in and of themselves. The composition of a research team and its collaborative efforts are critical factors for success. I believe that better results are born by building good relationships with colleagues and cooperating with each other. In the research laboratory, there are people in various positions, such as students, postdoctoral fellows, and professional researchers. To create an environment where each of them can grow and demonstrate their abilities, it is important to understand and respect their individuality and abilities. I myself am by no means a perfect person; therefore, I always want to learn from the people around me and grow together. Believing in and valuing the power of people's hearts is one of the most important things in research activities and in life.

▶ How do you spend your holidays?

I spend most of my days off with my children. Playing together is the most enjoyable and refreshing time for me. I used to have time to enjoy my hobbies, such as watching baseball games, running, and cycling. However, after my children were born, such time became scarce. Nevertheless, spending time with them gives me more fulfillment and joy than my previous hobbies.

▶ Lastly, could you share a few words about Samco?

I believe that Samco is an important company that supports Japan's semiconductor technology. I respect Samco's work in a wide range of fields, from research to production. It is especially noteworthy that they are applying the technology cultivated in production equipment to the field of research and development. High-quality equipment is an important factor that significantly influences research results. Samco's equipment captures the needs of researchers and provides high reliability and performance. The organization's dual focus on production and research allows it to develop equipment that meets the industry's high-level demands. I hope that Samco will continue to support researchers by providing equipment that supports cutting-edge research and development. I look forward to their continued success.

Thank you very much for taking time out of your busy schedule to talk with us.

> **"Samco's equipment captures the needs of researchers and provides high reliability and performance. The organization's dual focus on production and research allows it to develop equipment that meets the industry's high-level demands."**

1 K (Kelvin) = C (Celsius) + 273.15. 1 mK corresponds to an extremely low temperature of -273.149°C.

2 Takeda Shingen (1521-1573), the "Tiger of Kai," was a powerful and brilliant feudal lord famed for his military strategies, his rivalry with Uesugi Kenshin, and his adherence to the "Fūurinkazan" battle standard inspired by Sun Tzu's *The Art of War* during Japan's Sengoku period.

3 Shingen's philosophy of "nation building" was "People are the castle, people are the stone wall, people are the moat, compassion is an ally, and enemies are enemies." He believed that the whole country was a castle, and the harmony of people was comparable to the steepness of mountains and rivers. In fact, throughout his life, he never allowed the enemy to set foot in Kai. *From Yamanashi Prefecture Kofu City Website*.

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