Chinese team achieves room-temperature single-electron quantum memory breakthrough

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A research team at Fudan University has developed a two-dimensional single-electron memory device that achieves the theoretical limit of information density, namely one electron storing one bit of data, while operating stably at room temperature, marking a significant advance in next-generation memory technologies for Artificial General Intelligence (AGI).

The study, titled "Robust Single-Electron Memory with Quantum States Manipulation", was published in the journal Science on July 16 by a team led by Peng Zhou and Chunsen Liu from the National Key Laboratory of Integrated Chips and Systems and the School of Microelectronics at Fudan University (Figure 1).[1]

Based on a coplanar drain-channel-source (DCS) architecture, the researchers designed and fabricated a two-dimensional single-electron memory capable of producing a nonvolatile threshold-voltage shift of 0.5 volts triggered by a single electron at room temperature. The work marks the first time that stable and repeatable quantum memory behavior has been observed under room-temperature conditions. The researchers also identified two previously unknown quantum programming phenomena and an unprecedented quantum storage effect.

Memory chips are among the most critical components of modern computing systems. They must not only deliver data to processors at extremely high speed but also preserve enormous amounts of information after power is removed.

The Fudan team has been tackling this challenge for years. In April last year, the researchers reported in an essay published in Nature a memory device known as "PoX" that achieved ultrafast nonvolatile storage in just 400 picoseconds — the fastest electronic memory speed ever reported.[2-3] The work resolved a longstanding dilemma that had persisted since the invention of the floating-gate transistor in 1967: conventional memory technologies had struggled to combine ultrahigh speed with nonvolatile data retention.

Their latest study was aimed at solving another fundamental problem, namely how far can memory density be pushed?

In theory, the electron, as an indivisible fundamental particle, represents the smallest possible carrier of digital information. A memory that stores information using individual electrons—known as single-electron memory—would therefore reach the ultimate physical limit of storage density.

For decades, however, researchers regarded the concept as theoretically attractive but experimentally unattainable because it depends on the quantum behavior of individual electrons.

If a memory device is compared to a reservoir, each electron is equivalent to a single drop of water. According to the Heisenberg Uncertainty Principle,

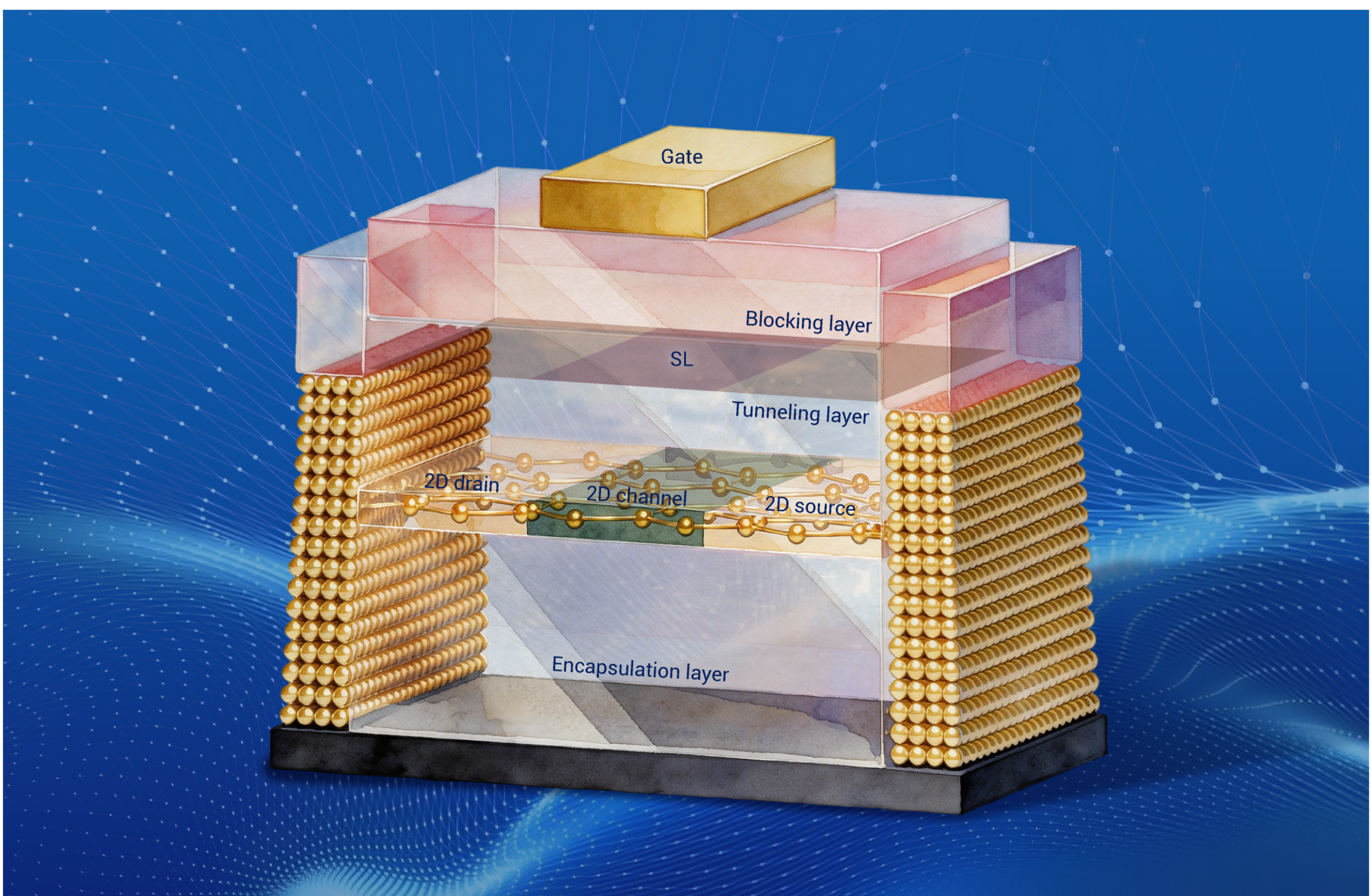

Figure 1. Schematic diagram of a two-dimensional single-electron memory device at room temperature.

confining an electron to an increasingly smaller space leads to larger energy fluctuations and stronger quantum effects, making stable control extraordinarily difficult.

Attempts to demonstrate single-electron memory in the late 1990s achieved only limited success. Earlier experiments detected voltage shifts of only a few tens of millivolts generated by a single electron, while the stored quantum state disappeared in less than five seconds.

To overcome these limitations, the Fudan researchers returned to the fundamentals of quantum mechanics and re-examined the physical limits of manipulating individual electrons.

Taking advantage of the atomic-scale thickness of two-dimensional semiconductor materials, which naturally confine electrons, the team developed an original self-aligned planar patterning approach and created what they call the "Guiyi" (Return-to-One) coplanar drain-channel-source structure.

Experiments showed that injecting just a single electron produced a storage window as large as 0.5 volts while maintaining stable data retention at room temperature, approximately 27 C.

Compared with the silicon-based single-electron memory reported by Science in 1997, which generated a voltage shift of only 55 millivolts lasting less than five seconds, the new device amplifies the room-temperature quantum-state signal by nearly an order of magnitude while achieving genuine nonvolatile storage.

The achievement pushes charge-storage density to its theoretical limit, realizing the long-sought goal of "one electron, one bit". Researchers believe it could provide a new technological foundation for developing ultrahigh-density memories needed by future AGI systems.

HOW THEY REALIZED THE ONCE-CONSIDERED IMPOSSIBLE

The breakthrough is the culmination of nearly eight years of continuous research.

In 2018, the team built a two-dimensional semi-floating-gate flash memory using multiple layered two-dimensional materials, increasing access speeds to around 10 nanoseconds. The work, published in Nature Nanotechnology, marked the group's first major achievement in flash-memory technology.

Although the device demonstrated impressive speed, its architecture was highly complex and retained data for only about 10 seconds after power was switched off. The researchers continued refining the technology and eventually found that flash memory itself could support both rapid reading and writing without sacrificing performance. Around 2024, they successively solved a series of technical challenges, including charge-polarity control and electric-field engineering.

Building on those advances, the team developed the PoX device. Within six months, they successfully integrated the technology into standard CMOS fabrication processes and produced a fully functional hybrid flash-memory chip known as CY-01.

The prototype overcame one of the major engineering obstacles facing emerging two-dimensional information devices and demonstrated the feasibility of industrializing chips compatible with conventional CMOS silicon manufacturing.

Nature described the achievement as an "original breakthrough", and it was later selected as one of China's Top 10 Scientific Advances of 2025.

Drawing on those earlier accomplishments and more than a year of intensive research, the team has now developed the Guiyi structure, breaking through the theoretical limit of information density in memory devices.

During the research, the scientists also proposed an original theoretical framework known as the "density-of-states scissors", which describes a previously unknown quantum storage phenomenon in which a pair of invisible "quantum scissors" selectively removes specific quantum states in energy space, causing them to disappear in a precisely controlled manner.

According to the researchers, the discovery not only establishes a new theoretical framework for single-electron quantum memory but also provides an important missing piece for translating quantum storage from fundamental physics into practical engineering.

With one electron representing one bit of information, the device has reached what the researchers describe as the ultimate limit permitted by quantum theory.

The next stage of the project will focus on engineering optimization and large-scale chip integration, with the goal of transforming the laboratory breakthrough into commercially viable semiconductor technologies for future high-density computing systems.

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DECLARATION OF INTERESTS

The author declares no competing interests.