Success in High Precision Control of Nuclear Spins for Quantum Computation

NTT in collaboration with the Japan Science and Technology Agency (JST) has successfully demonstrated coherent control over nuclear spins using a semiconductor nanoscale device. This development is expected to play a key role in creating quantum bits for quantum computers.

The nuclear spin controlling device was constructed by combining a point contact, which is a standard semiconductor nanodevice, and an antenna gate for applying electromagnetic radiation. The device was made using lithographic technology and was used after being cooled down to 80 mK. By applying a vertical magnetic field and controlling the electron density, we were able to create special conditions where the electrons interacted strongly with the nuclear spins. By passing an electrical current through the structure, we caused nuclear spins to be selectively polarized in the point contact region where the current density was high. Furthermore, the electrical resistance of the point contact showed changes that were approximately proportional to the magnetization originating from the nuclear spins. Accordingly, after the nuclear spins in the point contact region had been polarized by the current, when an alternating current was driven through the antenna gate to apply electromagnetic radiation at the NMR frequency, coherent nuclear spin oscillations occurred only at the desired transition. This resulted in oscillations of the nuclear spin magnetization, which could be detected from resistance changes in the point contact.

In these measurements, strikingly clear oscillations were observed corresponding to all transitions between four possible nuclear spin states of each nuclide (namely, ^{69}Ga, ^{71}Ga, and ^{75}As) present in the point contact structure. This new NMR technique, based on a nanodevice using resistance for detection, is highly sensitive and precise, allowing various coherent oscillations between four spin states to be clearly distinguished. In the experiment, coherent oscillations were observed for all possible types of transition (6 types) for each nuclide, giving 18 in total for the whole device. By manipulating the various coherences of the device, we will be able to make solid-state quantum algorithms and take further steps toward achieving a real practical quantum computer.

The number of nuclei in the point contact region was less than 10^8, compared with 10^{11}–10^{13}, which is the sensitivity limit of standard NMR technology, meaning that quantities 3 to 5 orders of magnitude smaller were detected. Furthermore, since the magnetization was directly measured, transitions between states separated by more than one quantum (unit) of spin, invisible in standard NMR, were readily detected. These results show that this is a fundamentally new technology for high-sensitivity, high-precision NMR. Moreover, since successful coherent control of nuclear spins has been achieved in a semiconductor nanodevice, other new systems can be expected to become possible for use in quantum computation where multiple spin states are freely and precisely controlled.

In the future, technology such as that for controlling interactions between nuclei and extending coherence times will be developed in order to construct further groundbreaking devices exploiting coherent control in nanodevices for application to quantum information processing systems.

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