Press Release

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Nippon Telegraph and Telephone Corporation
Japan Science and Technology Agency

Success in high precision control of nuclear spins for quantum computation

- New super-sensitive NMR (nuclear magnetic resonance) technology established -

Nippon Telegraph and Telephone Corp. (NTT; Head Office: Chiyoda-ku, Tokyo; President: Norio Wada) in collaboration with the Japan Science and Technology Agency (JST; Kawaguchi, Saitama, President: Kazuki Okimura) have successfully demonstrated coherent[*1] control over nuclear spins[*2], which are expected to be highly suitable for quantum computation[*3] as quantum bits[*4], using an all-electrical semiconductor nanoscale device, and furthermore, demonstrated coherent oscillations with all possible transitions in all constituent nuclides (types of nuclei) of the device. The nuclear spin controlling device is constructed by combing a point contact[*5], which is a standard semiconductor nanodevice, and an antenna gate for applying electromagnetic radiation. The present work clearly demonstrates that the device is highly suited as a nuclear spin based quantum information processing device. By manipulating the various coherences of the device, solid-state quantum algorithms will become possible and further steps can be taken toward achieving a real practical quantum computer.
The present achievements are results of collaborative research between NTT Basic Research Laboratories and JST"Quantum Coherent System Based on Carrier Interactions" (Research Coordinator: Yoshiro Hirayama, NTT Basic Research Laboratories, Executive Manager of the Physical Science Laboratory), and will be published in the 21st April issue of the British journal *Nature* (ref.1).

Background

A quantum computer, that makes use of the principles of quantum mechanics, is expected to exceed the performance made available by even the fastest classical computer and perform huge calculations in parallel at ultra high speed. As such, elements to build a quantum computer are being ferociously pursued by laboratories around the world. A real practical quantum computer is taken to require more than 10,000 qubits, rendering solid-state elements such as semiconductor or superconducting devices the most promising candidates due to their scalability. Among these solid-state possibilities, the nuclear spin qubit, which preserves coherence over much longer time-scales compared to other qubit systems, is thought to be one of the real eventual winners. However, all-electrical control and detection of nuclear spins at high sensitivity and precision had not previously been achieved, let alone at nanoscopic size-scales.

The Experiment and Results

The nanodevice used for the experiments consisted of a point contact formed by using split gates above electrons confined in a high quality GaAs quantum well, where the

central active region has nanoscale dimensions of 200nm x 200nm x 20nm (Figure 1). The device is made using lithographic technology and is used after cooling down to an absolute temperature of 80mK in a refrigerator. By applying a vertical magnetic field and controlling the electron density using the back gate, special conditions can be achieved where the electrons interact strongly with the nuclear spins. The split gates are then used to remove electrons from beneath them, leaving electrons under the special conditions in the form of a point contact. By passing an electrical current through the structure, nuclear spins can be selectively polarized in the point contact region where current density is high. Furthermore, the electrical resistance of the point contact shows changes that are approximately proportional to the magnetization originating from the nuclear spins. Accordingly, after the nuclear spins in the point contact region are polarized by a current, if an alternating current is driven through the antenna gate to apply electromagnetic radiation at the NMR[*6] frequency, coherent nuclear spin oscillations occur only at the desired transition, resulting in oscillations of the nuclear spin magnetization, which in turn is detected by the resistance of the point contact.
In these measurements, strikingly clear oscillations were observed reflecting 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. Figure 2 shows the observed coherent oscillations in ^{75}As. The result shows that 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.
The number of nuclei in the point contact region is under 10^8, compared with 10^{11}-10^{13} which is the sensitivity limit of standard NMR technology, meaning that 3 to 5 orders of magnitude smaller quantities are being detected. Further, since the magnetization is being directly measured, transitions between states separated by more than one quantum (unit) of spin, invisible in standard NMR, can now be readily detected. These results show that this is fundamentally new technology, for high sensitivity, high precision NMR. Moreover, since successful coherent control of nuclear spins has been achieved in a semiconductor nanodevice, further new systems can be expected to be made possible for use in quantum computation where multiple spin states are freely and precisely controlled.

Future developments

Technology such as 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 in quantum information processing systems.

Ref.1. G. Yusa, K. Muraki, K. Takashina, K. Hashimoto, and Y. Hirayama, "Controlled multiple quantum coherences of nuclear spins in a nanometre-scale device"(NTT Basic Research Laboratories and SORST-JST), *Nature* **434**, 1001-1005 (21st April 2005).

Press release by *Nature*

Techniques: NMR nanodevice (pp 1001-1005; N&V)
A tiny new nuclear magnetic resonance (NMR) device is presented in this week's Nature. To make the nanodevice, Go Yusa and colleagues fabricated a semiconductor structure that is electrically controllable. As such, the new device is self-contained,

eliminating the need for the large electromagnetic pick-up coils used in conventional NMR techniques.

Standard NMR spectroscopy - used extensively across the biological and physical sciences for structural imaging and fundamental studies - tracks a quantum mechanical property of nuclei called spin. The new system makes it possible to detect the spins directly with high sensitivity. Moreover, it enables access to quantum mechanical states normally 'invisible' to standard NMR, formed from superpositions of multiple spin levels. The ability to detect such states makes the nanodevice potentially suitable for applications in quantum information processing. In the nearer term, it may facilitate studies of confined, interacting electrons, and possibly also protein spectroscopy.

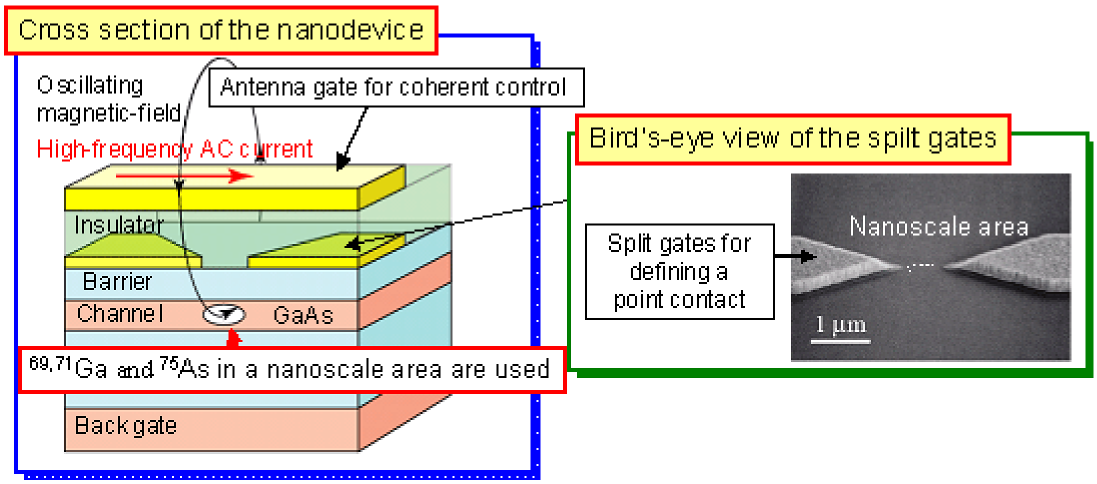

Figure 1. Schematic diagrams illustrating main aspects of the semiconductor-based point contact device used for coherently controlling nuclear spins in a nanometre-scale region.

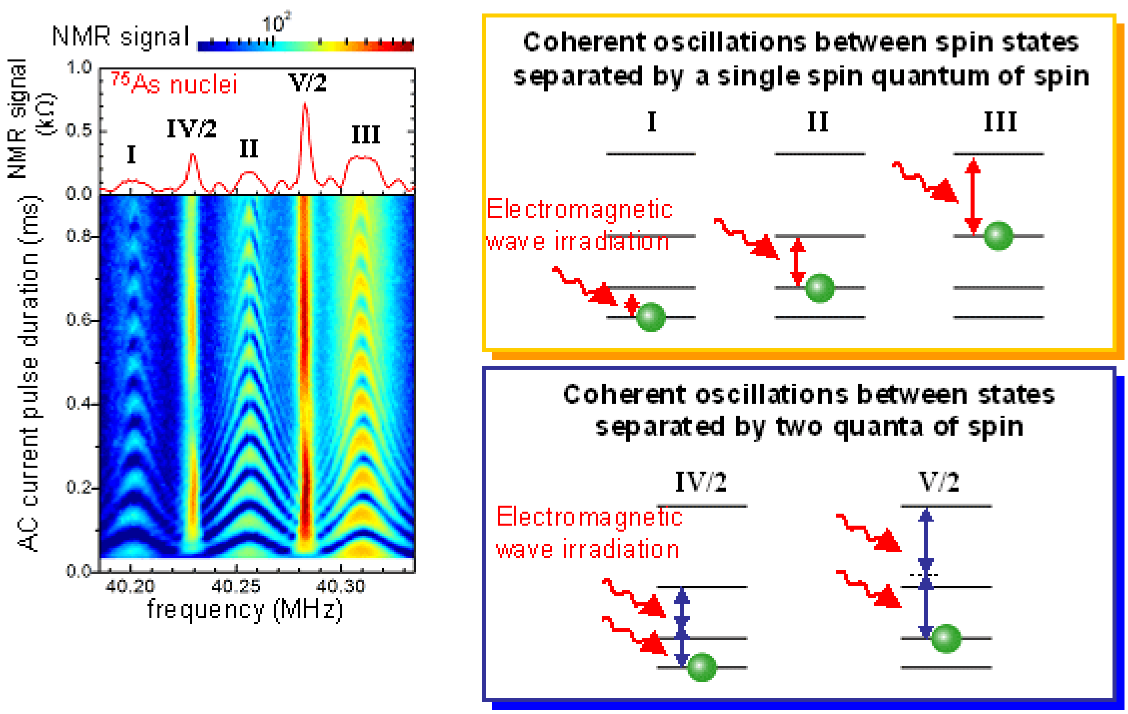

Figure 2. Coherent oscillations originating from various transitions between 4 spin states observed near the NMR resonance frequency of ^{75}As. Coherent oscillations between states separated by 3 spin quanta (triple-quantum-

coherence) were also observed when the strength of the radiation was increased by driving greater alternating current through the antenna gate.

Glossary

*1. **Coherence**

This is the degree to which the oscillating quantity, namely the quantum mechanical state, maintains a near constant phase relationship. In general, coherence will decrease exponentially with time as a result of the noise originating from outside the system.

*2. **Nuclear spin**

Nuclei are charged particles, and as such, their rotation can cause them to behave like tiny bar magnets. (Quantum mechanical properties of individual protons and neutrons making up the nuclei also contribute.) The quantity used to describe this property is known as nuclear spin. The behaviour of nuclear spin depends on the type of nuclei and their surroundings, allowing highly sensitive analytical techniques such as NMR to be made possible. As can be expected from the fact that an old and widely used technique of NMR relies upon coherent oscillations of nuclear spins, nuclear spins have a unique property of being robust, retaining coherence over relatively long periods of time, and is considered a highly favourable candidate for use as quantum bits.

*3. **Quantum computer**

A quantum computer is a computer that processes information by performing operations with a set of multiple quantum bits (quantum register). Parallel computation is possible in a quantum computer, because the quantum states can be superposed during calculations. If we obtain full control of n qubits, we can exponentially reduce the number of logical steps needed for a given calculation. For example, the quantum computer would require of the order of n steps while a classical computer would need 2 n steps. Exponential speedup is therefore possible.

*4. **Quantum bit (Qubit)**

This is the fundamental building block of a quantum computer. 'Qubit' is another name for a quantum two-state system. It is called the 'qubit' in analogy with the classical 'bit', which can have only one of two states 0 or 1. During calculation, the qubit can be in any arbitrary superposition of |0> and |1>.

*5. **Point Contact**

A structure in which two regions of electrons confined in a plane (2-dimensional) are connected through a narrow constriction or point (small region). The electrical behaviour of the structure depends upon the properties of the small region. Structures such as quantum dots are often constructed out of these point contacts and they constitute one of the basic building blocks of nanotechnology.

*6. **Nuclear magnetic resonance (NMR)**

A well-established technique used for extracting information regarding types of nuclei present in a sample, or chemical and structural details surrounding nuclei. It utilizes coherent oscillations caused by electromagnetic radiation exactly matching the energy separation between nuclear spin states. Usually, large pickup coils detect nuclear spins as they coherently rotate in response to applied radiation. Fore these measurements, at least 10^{11} nuclei are required.

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