(News release)

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Nippon Telegraph and Telephone Corporation
Japan Science and Technology Corporation

Potential application to quantum computer memories of the electron-spin characteristics of an artificial atom

- Toward an electron-spin quantum computer -

The Nippon Telegraph and Telephone Corporation (NTT), and the Japan Science and Technology Corporation (JST), in collaboration with the University of Tokyo and the National Research Council of Canada, have demonstrated the potential application of a semiconductor artificial atom (*1, Fig. 2) to the memory (quantum bits, *3) of a quantum computer (*2). This is a step forward to realize a practical quantum computer. Novel electrical pump-and-probe experiments (Fig. 3) are performed on an artificial atom that contains a controllable number of electrons. Electrons can be injected and collected accurately in time, and this reveals a clear selection rule (*5) for electron-spin (*4) for transitions in an artificial atom. This spin selection rule, which also appears in natural atoms, suggests electron-spin in an artificial atom can be preserved for a sufficiently long time that it can act as a memory to describe "0" or "1" in a quantum computer.

<Introduction>

An electron possesses intrinsic angular momentum ("spin"), and so behaves like a small magnet. Electron-spin, which is not utilized directly in conventional electronics, is now receiving much attention for future applications to novel electronic devices like magnetic sensors, and quantum computers that would provide extremely fast parallel data processing. The quantum computing scheme is quite different from the normal computing scheme, and requires hardware technologies for (1) memory (quantum bits) that store quantum information, (2) quantum logic gates (*6) that operate on the memory, (3) read-out devices for each memory bit, (4) integration of these devices, etc. One of the challenging requirements is to preserve the quantum information in the memory for a sufficiently long time to perform all the quantum processing. Many kinds of quantum computing schemes have been proposed, and some have even been studied experimentally for basic research. An electron-spin quantum computer, in which electron-spin in a semiconductor artificial atom is used as a memory unit (quantum bit), is one of the best candidates, because it is expected to have a long relaxation time. Our new results experimentally prove that the energy relaxation time (*7) of an electron-spin is extremely long.

<Experiments and results>

The experiments demonstrate that electron-spin in an artificial atom has similar characteristics to electron-spin in natural atoms, and indicates its potential application for a quantum computer. The experiments are carried out on an artificial atom, in which the number of electrons can be accurately controlled by an external voltage, using a novel electrical pump-and-probe technique. Electrons can be injected and extracted accurately in time, and this allows us to deduce the energy relaxation time, which is one of the most important characteristic times for quantum computing.

The artificial atom we study is a semiconductor nano-structure fabricated by electron-beam lithography, and has the desirable property that the number of electrons in the artificial atom can be changed one-by-one exactly starting from zero. It is called an artificial hydrogen atom if it has just one electron, and an artificial helium atom if it has two electrons.
The electrical pump-and-probe technique developed for this work allows us to control the injection and ejection of electrons into and out of the artificial atom very precisely in time. Note that this technique avoids the problem of conventional optical measurements that create electron-hole pairs. The energy relaxation time is investigated directly with this technique.
We measure the energy relaxation time from the first excited state to the ground state and the results are now summarized.

(1) The energy relaxation time of the artificial hydrogen atom is 3-10 nano-seconds.
(2) The energy relaxation time of the artificial helium atom is 0.2 milli-seconds.
(3) The ratio between these times is 20 - 60 thousand.

This large difference comes from the fact that electron-spin is well preserved in an artificial atom, so the energy relaxation of the excited artificial helium atom that involves a spin-flip is significantly less frequent than the relaxation of the excited artificial hydrogen atom that does not involve a spin-flip. A similar difference appears from selection rules in the optical transitions of natural atoms (real hydrogen and helium atoms). Our result can be understood as a selection rule for electron-spin. The extremely large difference also indicates the high quality of our artificial atom.
Based on these experiments, we deduce the energy relaxation time of the spin of a single electron to be more than 1 milli-second. This time is much longer than a typical period required for quantum logic gate operation (a few pico-seconds from literature), indicating the potential application of electron-spin for a quantum computer.

<Future prospect>
We will search for quantum logic gates and read-out techniques for electron-spin, and continue the drive for the realization of a practical quantum computer.

This work will be published in Nature (19th of September 2002 issue, embargoed until 1900 hrs London time on 18 September).

<Definition of terms>
***1 artificial atom**: A quantum dot is a nano-meter scale artificial structure made from semiconductors. A quantum dot holding a few electrons is commonly referred to as an artificial atom since it shows atomic-like behavior.

***2 quantum computer**: A quantum computer, which processes massive calculation very efficiently in parallel by using quantum mechanics, is expected to surpass normal computer performance for some specific tasks. Nuclear magnetic resonance (NMR) quantum computers with liquid molecules are the most advanced hardware at present. However, solid-state quantum computers are demanded for large-scale integration. An electron-spin solid-state quantum computer is one of the best candidates.

***3 quantum bit**: The unit of quantum information used in a quantum computer is called as quantum bit, and is the quantum analogue to a classical bit that represents "0" or "1" at any time. The quantum bit can be a superposition of states "0" and "1", for example, there is a 30% probability of it being "0" and a 70% probability of it being "1".

***4 electron spin**: An electron is an elementary charge that can carry a current, but it also behaves like a small magnet due to the electron's intrinsic angular momentum ("spin"). Recently fundamental research on the application of electron-spin has dramatically intensified.

***5 selection rule**: In natural atoms, optical transition from one state to another is possible only for specific combinations of states as determined by selection rules. One of the selection rules is that electron-spin is conserved during a radiative transition. Our results concern the spin selection rule in an artificial atom.

***6 quantum logic gate**: Quantum logic gates are the basic blocks of quantum information processing in a quantum computer. Any quantum computing program can be performed with combinations of just a few types of quantum logic gates.

***7 energy relaxation time**: The energy relaxation time is the time required to change from a high-energy excited state to the low-energy ground state, and can be regarded as the retention time of the information memory.

	conventional computer	electron-spin quantum computer
feature	large-scale integrated multipurpose computer	high-speed parallel computer based on quantum mechanics
example of information storage	voltage, charge, etc. (bit)	direction of an electron spin (quantum bit)
information processing	logic gates (NOT, AND, OR, etc.)	Quantum logic gates

Fig. 1 Comparison between a conventional computer and an electron-spin quantum computer.

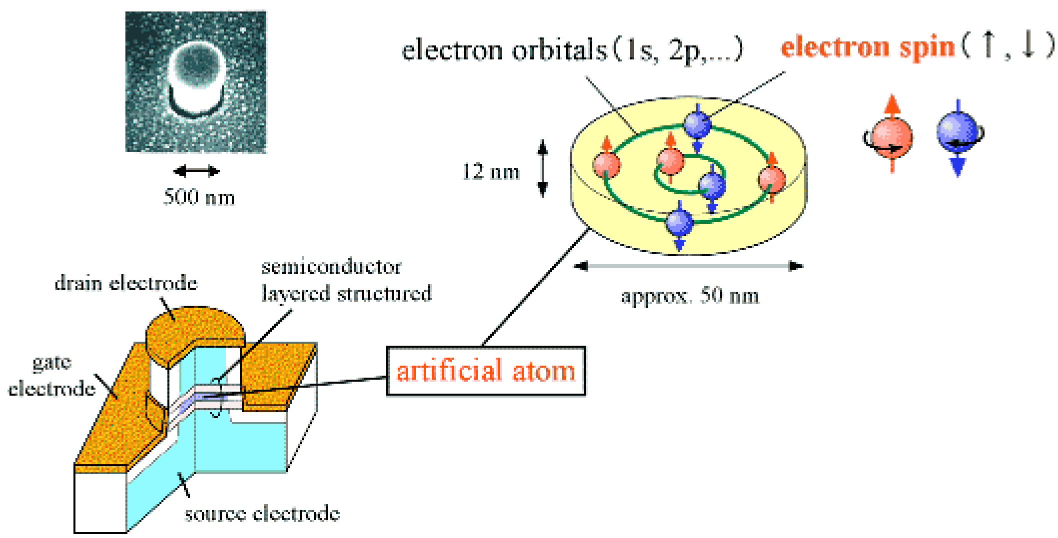

Fig. 2 Semiconductor artificial atom

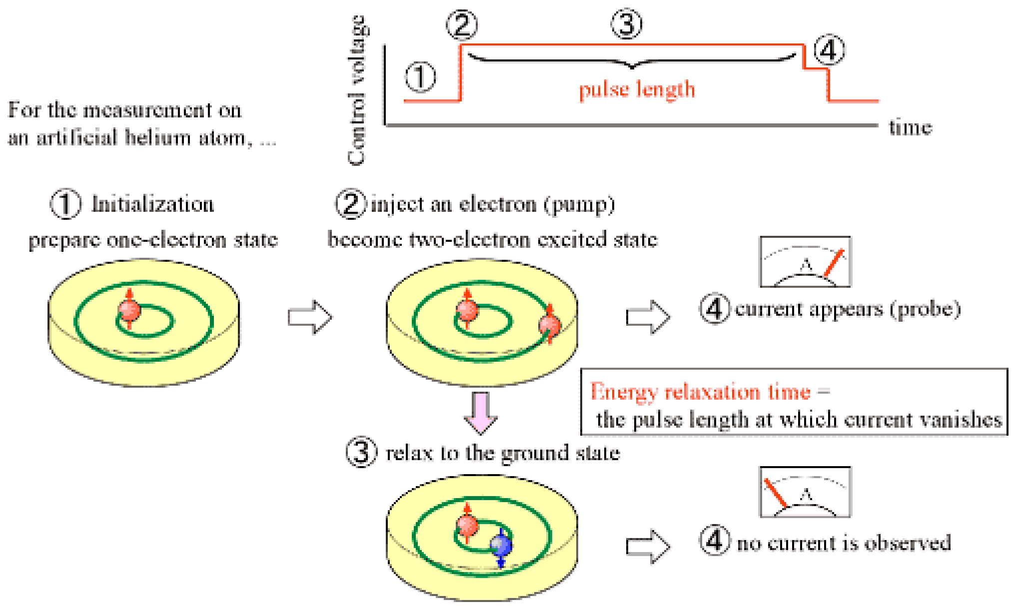

Fig. 3 Electrical pump-and-probe experiment

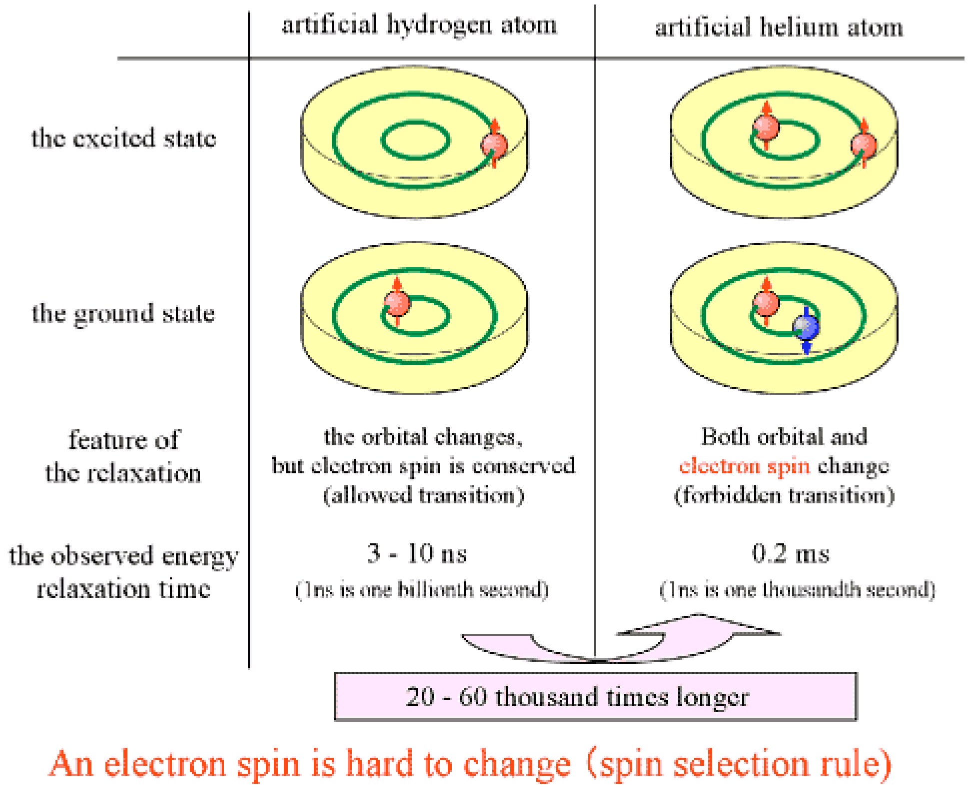

Fig. 4 The experimental results of the energy relaxation times in artificial atoms.

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