# Quantum Information Technology based on Single Electron Dynamics

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## Abstract

Quantum information technology promises powerful information processing based on the control of the dynamics of individual particles. Research on single electron dynamics aiming at the coherent electrical manipulation of single electron charge and spin in semiconductor quantum dots is expected to provide practical quantum information technology. A single electron charge quantum bit (qubit), which has recently been realized in a double quantum dot, is advantageous for flexible control of the quantum state by a high-speed electrical signal, while a single electron spin qubit is expected to have a sufficiently long decoherence time. This paper reviews our research on single electron dynamics for quantum information processing.


## 1. Introduction

Quantum information technology seeks to manipulate quantum states by coherent time evolution, in which the bases of the quantum state are regarded as digital information. By analogy to a bit, the unit of classical digital information, the unit of quantum information is a quantum bit (qubit), which can basically be realized in any single two-level system. Various types of information processing based on qubits have been proposed and demonstrated [1]. Quantum information technology provides various advantages that could never be obtained in the conventional classical approach. One would be secure telecommunications through quantum cryptography because an unknown single quantum state can be neither duplicated nor determined completely. Another example is a quantum non-demolition measurement scheme, which would improve the accuracy of a quantum measurement by avoiding back action. Then there is the quantum computer, a programmable interferometer in which only one or a few desired answers can be efficiently obtained from an extremely large number of candidates. Recently, quantum information technology has become attractive for very specific tasks.

Although the potential of quantum computing is fascinating, only a few small-scale quantum computers have been built. Practical quantum computing hardware with a large number of qubits is strongly desired. Recently, coherent control of quantum states in a nanostructure has been attracting growing interest for flexible control of many qubits [2]. Single electron dynamics, which describes the dynamical response of a single-electron in nanostructures, is one of the best candidates for useful quantum information technologies [2], [3]. Here, we review our research activities and strategies on single electron dynamics and discuss its prospects for future quantum information technology.

## 2. Concept of quantum computation

In quantum information technology, a quantum state is a carrier of information. It is transformed from an initial input state to a final output state by applying an external field, *e.g.*, an electromagnetic field, for a certain period. The fundamental transformation of the quantum state is called a quantum logic gate, and it should be a unitary transformation to keep coherency. The quantum state is changed by applying a series of quantum logic gates for the start of quantum computation, when classical digital information is input to the quantum state, until the end of the computation, when the output states are finally measured as classi-

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cal information. One may not measure the intermediate state, because that would cause the quantum state to collapse. Quantum computing requires that a high degree of quantum coherence be maintained for a long enough time to complete the computation. One can design an algorithm for quantum computation in such a way that a series of data processing is performed simultaneously in a parallel fashion (quantum parallelism). Quantum computation is therefore expected to provide extremely efficient calculations for specific problems that cannot be solved efficiently with conventional classical computers.

To construct a quantum computer, a bunch of single quantum states must be (i) prepared physically, (ii) initialized, (iii) manipulated coherently, (iv) preserved for a long enough time, and (v) measured individually. Each of these requirements needs further development. Below, we briefly summarize our strategies for realizing quantum computers using single-electron dynamics.

## 3. Single-electron dynamics

A quantum dot is a small conductive island (less than 100 nm in diameter) that contains a tunable number of electrons occupying discrete orbitals. Figure 1 shows a scanning electron micrograph of representative samples containing from one to four quantum dots (schematically illustrated by circles). Since the electron filling in a quantum dot resembles that in normal atoms, quantum dots are often referred to as artificial atoms. For example, as is true for some atoms, a quantum dot containing a few electrons exhibits magnetic properties depending on the electron filling. Actually, quantum dots with a few electrons show spin-polarized states even at zero magnetic field. The great advantage of artificial atoms (quantum dots) is that the element of the artificial atom (H, He, Li, and so on) can be changed just by changing external voltages.

NTT Basic Research Laboratories have been study-

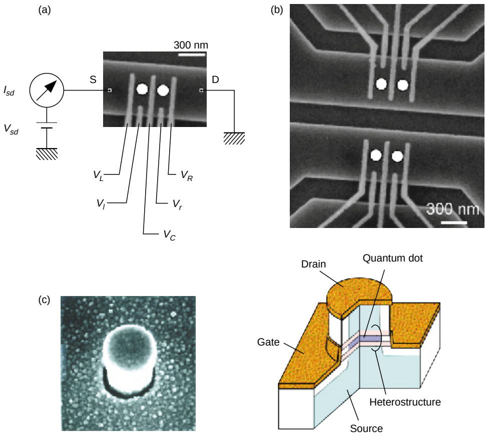


Fig. 1. Scanning electron micrographs of quantum dot devices. (a) Double quantum dot, schematically shown by two circles, fabricated by dry etching and fine metal gate patterning. (b) Two sets of double quantum dots (prototype device). (c) A vertical single quantum dot, in which the source and drain electrodes are located above and below the quantum dot.

ing the dynamical response of a single electron in a quantum dot, which is called single-electron dynamics. For instance, a single electron can be injected into or extracted from a quantum dot by applying a high-speed electrical signal with time accuracy better than 1 ns. The injection and extraction can be detected as a change in the charge on the dot with time accuracy better than 1 µs. Moreover, an electron in a quantum dot can be excited by applying microwaves, which corresponds to optical excitation in atoms. This research promises to provide novel semi-classical electronic devices that can precisely control and measure an electronic current. The more challenging and effective application of this research though is in quantum information technology, in which single electron charge and spin is controlled quantum mechanically. Single electron dynamics in quantum dots is expected to satisfy the requirements for quantum information technology and lead to useful quantum computers.

### 3.1 Charge quantum bit in a double quantum dot

Consider a double quantum dot, in which two quantum dots are separated by a tunneling barrier. The double quantum dot can be regarded as diatomic molecule: the two dots are coupled electrostatically (corresponding to an ionic bond) and quantum mechanically (corresponding to a covalent bond). The coupling strengths can also be controlled by external voltages.

Figure 1(a) shows a typical double quantum dot device fabricated in an AlGaAs/GaAs modulation doped heterostructure. The upper and lower dark regions are etched, and the adjacent region is depleted of conductive electrons. The bright vertical lines are metal gate electrodes used to deplete the underlying region. The resultant conductive islands (double quantum dot) are schematically shown by circles. The double quantum dot is attached to the source and drain electrodes and can be investigated by measuring the tunneling current.

Now, consider the situation where an excess electron is injected into the double quantum dot (See Fig. 2(a)). In the classical picture, the electron occupies either the left or right dot at any given time. This is analogous to the logical 0 and 1 of a classical bit. In the quantum mechanical picture, however, an electron behaves as if it occupies the left and right dots simultaneously (superposition of 0 and 1), but the probability of finding the electron in one of the dots is determined quantum mechanically. In quantum information technology, this probability is the quantum information itself, and should be manipulated or preserved during the calculation.

We have succeeded in controlling the quantum state of a double quantum dot by applying a high-speed electrical pulse (from 100 ps to 2 ns) to one of the electrodes [4]. The electron initially injected into the left dot moves back and forth between the two dots during the pulse, which corresponds to a sinusoidal oscillation in probability between 0% and 100%. The probability can be controlled by tailoring the pulse waveform and is obtained from the tunneling current under the repetition of many pulses. A specific pulse waveform that changes the probability from 0% to 100%, or from 100% to 0% can be used as a NOT gate, which

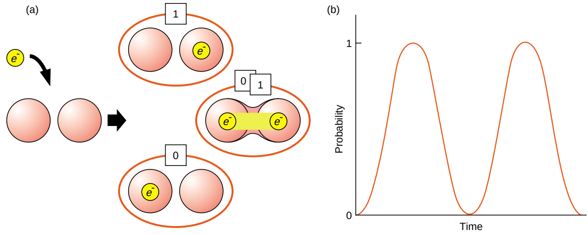


Fig. 2. (a) Quantum state of a single electron in a double quantum dot. When an excess electron is injected, it can occupy the left dot (0), right dot (1), or both dots simultaneously (0+1). (b) The probability of finding the electron in the right dot.

is the most fundamental quantum logic gate.

The next experiment would be two-qubit operation on two sets of double quantum dots (See Fig. 1(b) and Fig. 3(a)). The two double dots are coupled electrostatically to correlate the electron occupation in one double quantum dot with that in the other. For instance, the NOT gate operation at one double quantum dot can be performed only when the electron is located in the left dot of the other double quantum dot. This conditional NOT operation (controlled NOT gate) is another fundamental gate operation in quantum information technology. If it is performed coherently, the controlled-NOT gate should work for any superposition state as well. One can design any quantum algorithm by combining a few types of fundamental quantum logic gates (a universal set of logic gates).

Another important requirement for quantum information technology is the single-shot measurement, in which the electron occupation in the double quantum dot is determined by a single measurement. In this case, the measurement outcome is either 0 or 1, whose probability can be controlled by quantum logic gates. The electron occupation in a double quantum dot can be measured with a single electron transistor (SET), which can be fabricated near the double quantum dot by the same technique. We are developing a high-speed version of the SET, operated with a radio frequency signal (RF-SET), and expect it to work as a single-shot measurement device [5].

So far, basic technologies (NOT gate, controlled-NOT gate, and single shot measurement) for a charge qubit have been summarized (Fig. 3(a)). However, a serious problem for the success of quantum information technology is decoherence, the loss of the quantum information: the whole computation must to be finished within this decoherence time. For a charge qubit in a double quantum dot, the decoherence time is not very long, about 1 ns, at present. Solving this problem requires further investigation and refinement.

### 3.2 Spin qubit in a single quantum dot

The spin degree of freedom, which originates from the spinning of a charged particle, is an alternative way to construct a qubit. While the charge qubit is an artificial qubit, the electron spin is a natural one. The spin decoherence time of conductive electrons in bulk GaAs crystal can be longer than 100 ns, and electron spin bound to a donor in silicon shows a decoherence time of about 300 μs. Electron-spin based quantum computation is motivated by this long decoherence time. Coherent manipulation of electron spins has been studied in many systems. The easiest way is to use electron spin resonance, which involves applying a microwave magnetic field under a static magnetic

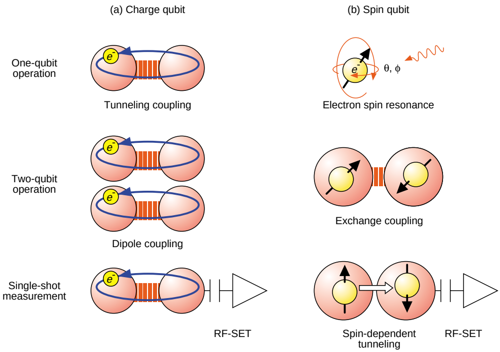


Fig. 3. Summary of quantum information technologies, one- and two-qubit operations and single-shot measurement, for (a) a charge qubit in a double quantum dot and (b) a spin qubit in a single quantum dot.

field.

However, in contrast to the countless studies on the ensemble of spins in many materials, little work has been done on the manipulation of single-electron spin. A quantum dot containing a single electron spin provides flexible quantum information storage (See Fig. 1(c) and Fig. 3(b)). We have developed a novel electrical pump and probe experiment for a quantum dot, and investigated inelastic spin relaxation time in a quantum dot containing a few electrons (Fig. 1(c)) [6]. We found that the energy relaxation time, which is the time necessarily to complete the quantum computation including the last measurement, can be longer than 200 μs for a realistic quantum dot structure. This result is very encouraging.

The NOT gate operation, which reverses the spin direction from up (0) to down (1) or vice versa can be performed using microwave irradiation (electron spin resonance). To address each electron spin (qubit) in many quantum dots, single-spin manipulation and measurement techniques are essential. The effective g-factor of each electron spin can be made different for different quantum dots through g-factor engineering, or a moderate magnetic field gradient is applied to the quantum dots, so that each qubit is addressed by a corresponding microwave frequency. However, a typical one-qubit operation using electron spin resonance requires a relatively long period of time, 100 ns for instance, because of the weak magnetic dipole interation. Alternative approaches, *i.e.*, using the optical Stark effect in a specific band structure or exchange coupling among three electron spins constituting one qubit, are suitable for much faster operations.

Two-qubit operation, which is required to construct a universal set of logic gates, is expected to be achieved by connecting two quantum dots with a tunable tunneling barrier. The exchange coupling between the two spins can be used to swap the two spins (SWAP gate). The controlled-NOT gate can be constructed by combining a NOT gate and a SWAP gate.

Single-shot spin measurement is a challenging technique for quantum information technology. One proposal is based on the spin-dependent tunneling between two quantum dots combined with an RF-SET. When each of the dots possesses one electron spin before the measurement, tunneling from one dot to the other is allowed, if the two electron spins can make a spin pair (spin singlet state). This spin-dependent tunneling could be measured with an RF-SET in a short time.

## 4. Future prospects

This paper has outlined our research activities and strategies on single electron dynamics for future quantum information technology. It was once believed that quantum mechanics can only appear in limited cases, such as in atoms, but this has been shown to be untrue, and many kinds of quantum mechanical behavior have been designed and observed in many different materials and devices. Recent nanofabrication techniques allow us to fabricate much smaller structures than our sub-micrometer double quantum dot. The combination of nanofabrication techniques and high-speed measurement techniques will lead to progress in quantum information technology. Another thing we should note is that single-electron dynamics is also attractive for novel semi-classical devices, such as a very sensitive electrometer and logic devices with ultimately low power consumption. The ideas arising from our research on quantum information technology might also improve the characteristics of these devices. We are confident that quantum information technology will offer valuable applications, even if they are very small scale.

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