Viewpoint

One, Two, Bits of Spin

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Combining operations with one and two spin qubits may lead to superior quantum computers.

Subject Areas: **Quantum Information, Mesoscopics, Spintronics**

A Viewpoint on:
Two-Qubit Gate of Combined Single-Spin Rotation and Interdot Spin Exchange in a Double Quantum Dot
R. Brunner, Y.-S. Shin, T. Obata, M. Pioro-Ladrière, T. Kubo, K. Yoshida, T. Taniyama, Y. Tokura, and S. Tarucha
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The last decade has witnessed amazing progress in the field of spin qubits, where a computer's bits are based on spin states of one or two electrons. Now, in a paper in *Physical Review Letters*[1], Roland Brunner at the Japan Science and Technology Agency and co-workers provide an important step forward. By way of background, it is interesting to consider the experimental situation in 1998 when Loss and DiVincenzo [2] proposed a quantum computer based on single spins in lateral quantum dots—puddles of electrons defined by electrostatic gates fabricated above a sheet of electrons—as qubits, utilizing oscillating magnetic fields for the one-qubit rotation and the exchange interaction to drive two-qubit operations. At that time the experimental status was not encouraging. Lateral quantum dot experiments were limited to a minimum of about 30 confined electrons. There was no technique available to read out information regarding single spins and perhaps the biggest basic challenge was the requirement of single-qubit addressability, i.e., the ability to rotate a single spin without disturbing its neighbors. The suggested solution for this issue, to incorporate a spatially varying g factor, seemed ambitious and has indeed proved difficult to implement.

Experimentalists responded impressively to these challenges. A new gate layout design [3] made the isolation of a single spin in each dot quite routine. A simple electrostatic invention that had been waiting a decade for an application [4] was found to be critical. This technique was originally considered a "noninvasive probe" but is now almost universally referred to as "charge detection." In this procedure the qubits are probed indirectly by measuring the current through a neighboring constriction. The electrons in the quantum dots control the current flowing through the constriction. Each time an electron is added to (removed from) a quantum dot, the current through the constriction is lowered (increased) via simple electrostatics. It was soon realized [5] that this concept was especially powerful in more complex devices involving multiple qubits since it was possible to track the transfer of electrons between dots. A Pauli blockade effect [6], based on the principle that two fermions cannot occupy the same quantum state, was invoked to extract spin information. Any attempt to transfer an electron into a quantum dot where the available orbital state is already occupied by an electron would only be successful if the two electrons had opposite spin. Any reluctance on the part of the electron to transfer due to the Pauli blockade would be detected by the above charge detection technique, thus identifying the spin sign.

The issue of addressability took longer to solve and there were several approaches. Electron spin resonance (ESR)—the single-qubit operation of the Loss-DiVincenzo scheme—was demonstrated in a seminal experiment [7] on a single spin in a quantum dot with a local resonant oscillating magnetic field. But this did not by itself solve the addressability issue, namely, why would this field not also affect neighboring spins. Not longer after, single-spin resonances were also demonstrated using electric dipole spin resonance (EDSR) techniques either by coupling to its momentum (via spin-orbit coupling) or to the hyperfine Overhauser field of nuclear spins. Pioro-Ladrière, Tarucha, and their co-workers [8], however, demonstrated a suggestion by Tokura *et al.*[9] to perform EDSR in a more controllable way by means of micron-size ferromagnets (see Fig. 1). The micromagnets were placed on top of the device, creating local field gradients across each quantum dot. Moving an electron temporally in the field gradient via electrical operations—the application of microwave electric fields—is equivalent to applying an oscillating magnetic field to the electron spin. Taking advantage of the condition that an electron spin rotates only when the oscillating frequency matches the local Zeeman field, addressability was achieved simply by shaping the micromagnets to produce local Zeeman

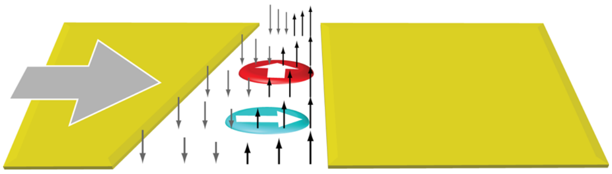

FIG. 1: A schematic of the device and magnetic fields involved in the experiment. An in-plane magnetic field (large grey arrow) is used to magnetize the split cobalt micromagnet (yellow). This results in magnetic field gradients (small grey arrows) across the quantum dots (blue and red disks). Microwaves applied to the micromagnet create spatial displacements of the electrons in the quantum dots. Single spin rotations occur when the microwaves are resonant with the local Zeeman fields. By shaping the micromagnets, which results in different gradients across each quantum dot, addressability of the two electron spins (white arrows) is achieved. (APS/Alan Stonebraker)

fields, different in each quantum dot.

Quantum computation requires a universal set of quantum operations. The single-qubit rotation, ESR or EDSR, is not sufficient—an additional entangling two-qubit operation (an operation that creates an output state where the two spins can no longer be considered separately) is required. Interestingly, progress towards the two-qubit operation was first achieved indirectly. In 2005, Petta and his colleagues at Harvard [10] demonstrated all-electrical coherent control of a double quantum dot qubit based on singlet and T^0 triplet spin states. An architecture based on capacitive coupling of pairs of quantum dots (each pair forming a single qubit) has been developed and makes this particular qubit a strong competitor. Moreover, the exchange interaction single-qubit operation that Petta *et al.* demonstrated was in fact similar to the two-qubit operation for the original single-spin qubit now considered by Brunner *et al.*[1].

In principle, both the technology and the individual experimental elements were now in place for someone to combine one- and two-qubit operations. This is exactly the achievement of Brunner *et al.*[1]. Before this work it was not clear that one could combine the specific exchange interaction based on a two-qubit operation (an operation formally called $\mathrm{SWAP}^{1/2}$) with the one-qubit operation, EDSR, in the nonuniform magnetic field produced by the micromagnets. Any gradient in the Zeeman splitting would induce an evolution between the singlet and the T^0 triplet spin states, which would modify the quantum operation. Brunner *et al.*[1] have, however, succeeded in demonstrating an impressively complex sequence of quantum operations involving specific single-spin rotations using micromagnet technology ($3\pi/2$ and $\pi/2$ rotations) and a two-qubit exchange interaction-based operation. Starting in an uncorrelated T^+ triplet state, they were able to create a partially entangled output. From a comparison with the calculated concurrence, they reasonably conclude that they have been able to modulate the degree of entanglement between their spins by the exchange operation time. While one can debate whether they have performed an ideal $\mathrm{SWAP}^{1/2}$ operation due to the Zeeman gradient, they have demonstrated that theirs is an entangling two-qubit operation and therefore can be employed for constructing more complex two-qubit operations such as the important CNOT operation.

Over the last decade, the experimental emphasis for spin qubits has been on demonstrating the required criteria for a viable scheme for quantum computing. This has been driven primarily by groups at Harvard and Delft universities. The next stage is to go to higher numbers of coupled qubits and demonstrate more complex quantum gate operations and algorithms. The paper by Brunner *et al.*[1] is a necessary step forward. It is clear that the spin qubit system currently lags behind other quantum computer implementation schemes. Solid-state based schemes, especially semiconductor ones, have always held the promise, however, that the enormous progress from decades of device integration technology development could one day lead to scalability not feasible with other schemes. To achieve this, however, we need parallel work on spin qubits in different materials to optimize coherence times, device designs, and architectures and to explore hybrid technology based on exploiting the most useful properties of different schemes.

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