All-Optical Electron Spin Quantum Computers
Using Precisely Ordered Quantum Dot Array Formed By AFM Lithography

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The solid-state qubits have scalability necessary for practical quantum computers. Electron system in semiconductor nanostructures has another advantage of good control of individual quantum states, which is particularly important in quantum gate operation. We have proposed all-optical operation scheme using electron spins in coupled quantum dots [1]. All single- and two qubit operations are switched on and off by coherent π-pulses which transfer electrons into neighboring dots (operation dots) as shown in Fig. 1 and Fig. 3(a). The spin is rotated (single bit case) or swapped (two qubit case) in operation dots. This swap operation is analyzed in detail in [2]. The spin state is detected indirectly by observing the elementary charge in the measurement dot using single-electron transistors. The spin-charge(orbital) entanglement is formed also by resonant π-pulse. The formation of (one- or two-dimensional) array of quantum dots whose sizes and positions are precisely controlled is a necessary technique for this scheme. We have succeeded in fabricating such finely controlled dots using atomic force microscope lithography [3].

Firstly, AFM lithography is used to fabricate nanoscale oxide on an n-GaAs surface. The oxide dots are subsequently etched off in diluted HCl and thus site-controlled holes are obtained as shown in Fig. 2. On the hole-patterned surface, QDs are regrown by molecular beam epitaxy. It is similar to the conventional Stranski-Krastanov (SK) growth but the coverage is below the point of transition from two to three dimensional growth.

The size fluctuation of 10% is obtained using this technique. This feature is as the best of conventional SK grown. The height and depth fluctuations, ~ 0.4 nm here, are reasonably small.

A cluster of coupled quantum dots with various sizes and exact positions are required in our scheme of quantum computer. Figure 3(a) shows two dimensional version of our cell layout. Using the present technique, we have fabricated differently sized and close-packed quantum dots on the same surface, as is shown in Fig. 3(b).

[1] T. Ohshima, Phys. Rev. A 62, 062316 (2000).

[2] T. Ohshima, Abstracts of 1999 Autumn JPS meeting (Sept.3, 1999), 25pA4; Jpn. J. Appl. Phys., Part1, No.4A, 41, pp.1963-1968 (2002).

[3] H.Z.Song et al., 26th Int. Conf. Phys. Semicon., (July 29-August 2, 2002, Edinburgh, UK), P32.

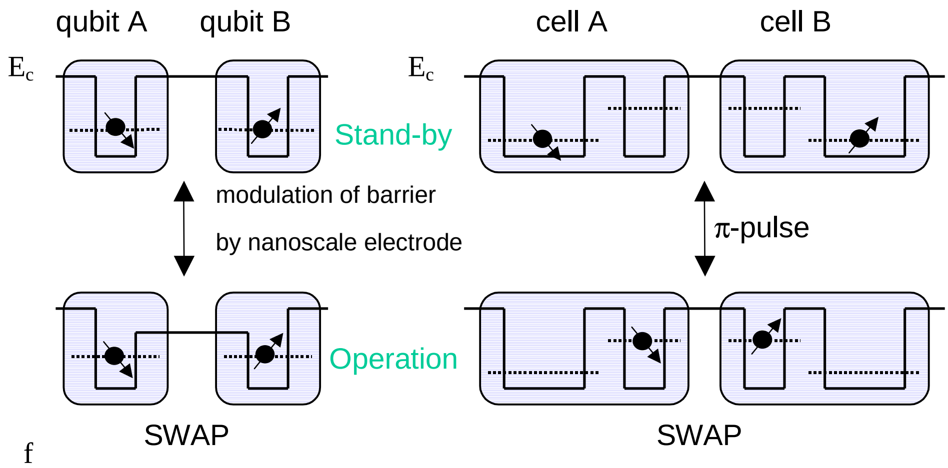

Fig. 1. All-optical operation scheme of electron spin qubits using coupled quantum dots.

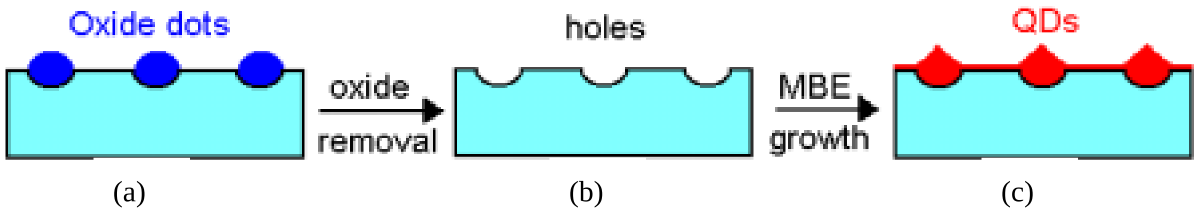

Fig. 2. Schematic cross sections of an array after (a) AFM oxidation, (b) oxide dots removing, (c) $In_{0.4}Ga_{0.6}As$ QDs regrowth..

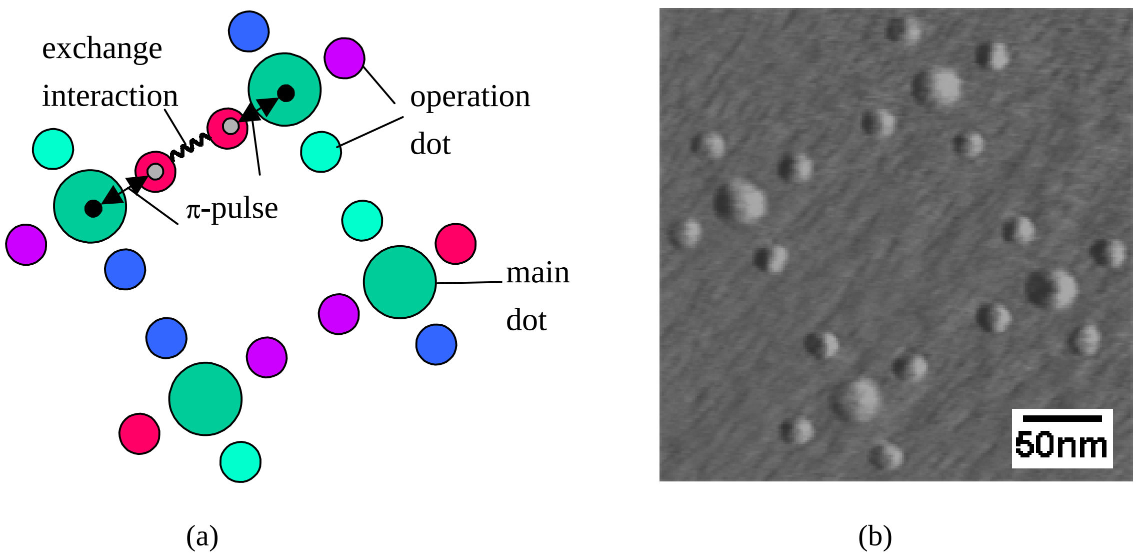

Fig. 3. Schematic two dimensional layout of qubit cells which contain five quantum dots (one large dot and surrounding four smaller dots) in each cell (a). Top-view AFM image showing a group of differently sized $In_{0.4}Ga_{0.6}As$ QDs fabricated by the present technique. The bigger and smaller QDs are ~30 and ~20 nm in diameter, respectively.