Single-electron Spin Coupling in Double Vertical Quantum Dots

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The spin of a single electron is suggested as a possible candidate for realizing a quantum bit (qubit) [1]. Using the electron's spin as a qubit has a few important advantages as compared to the electron's charge [2]. Most importantly, the single-electron spin decoherence time, T_2, is expected to be on the order of or larger than 100 ns, much longer than typical electron charge decoherence times (up to a few ns). This estimate is based on the decoherence time T_2^* of an *ensemble* of electron spins in GaAs.

Besides single spin rotation, the entanglement of two electron spins using tunnel-coupled quantum dots is of great importance for the realization of the controlled-NOT gate operation [1]. The combination of these two basic operations has been proven to be sufficient for creating a universal quantum gate. The ground state of two coupled electrons is a spin singlet at low magnetic field, which is an entangled spin state. It has been shown that the two-electron ground state can be changed to a spin triplet state using a static magnetic field *B* [3]. For a two-electron system the (*B*-dependent) singlet-triplet energy splitting corresponds to the exchange coupling, *J*, between two spins. By turning on and off *J* (e.g. by pulsing the coupling gate voltage), it should be possible to swap or entangle both electrons [2].

Here, we discuss our experimental approach for realizing single-electron spin qubits in semiconductor quantum dots, in particular the control of the exchange coupling between two electron spins in a double quantum dot. Our new sample design consists of a laterally coupled, double vertical dot system (Fig.1). Each dot can be individually addressed by line side gate electrodes. By feeding an AC current through each of these gates, an AC magnetic field can be generated in each dot in order to realize local single spin rotation. In our vertical dot system, it is possible to control the individual orbital states (s,p,d,…orbitals) and spin states in the few-electron regime by DC gate voltages and *B*. In addition, the overlap of the wave functions between both dots can be effectively tuned using the center gate voltage . Hence we can control the coupling between the dots *in situ*. By applying a pulsed coupling gate voltage at a suitable *B*, *J* can be switched on and off, since for a 2-spin system the tunnel coupling, *t*, is directly related to *J* by $J = 4t^2 / U - W(B)$, where *U* is the on-site Coulomb repulsion, and $W(B)$ accounts for the long-range Coulomb interaction [2].

We measure the fundamental electronic properties of our double dot system, using a single electron tunneling spectroscopy technique. We observe a charging diagram in the plane of the two side gate voltages (Fig.2), which is typical for two coupled dots in series [4]. From the analysis of the charging diagram we can derive the tunnel coupling between both dots for different settings of the center gate voltage and magnetic field. The present results form an encouraging basis for further investigation of controllable spin dynamics in our quantum dot systems.

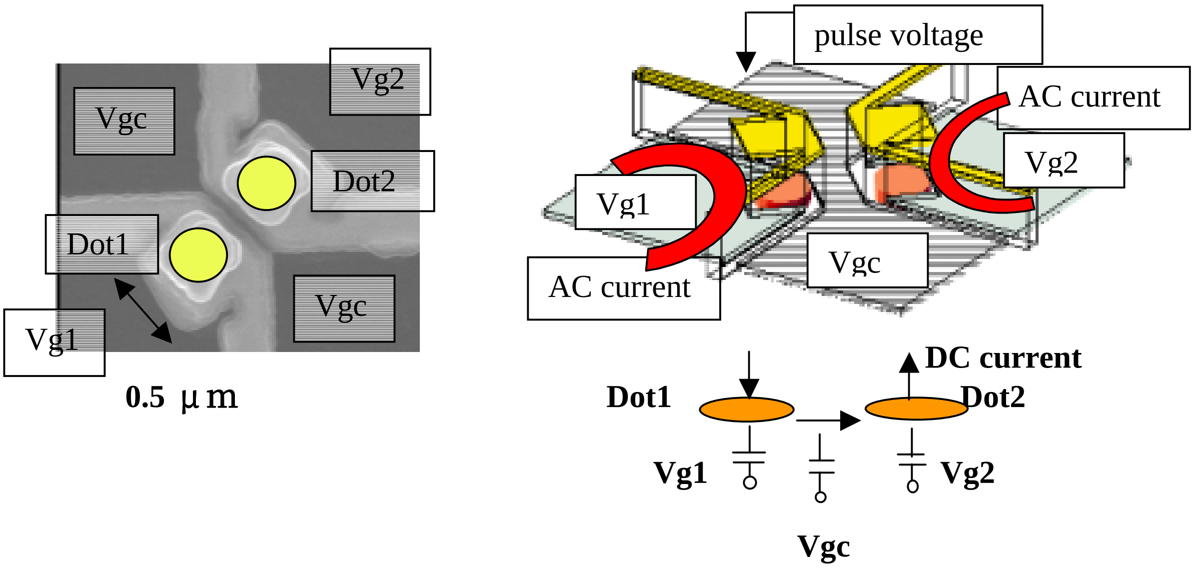

Figure 1. (a) SEM picture of the device. (b) Schematic picture of laterally coupled double vertical quantum dots. The dots can be addressed by individual side gate voltages V_{g1} and V_{g2}. The (tunnel-)coupling between the dots can be tuned using the center gate voltage V_{gC}. A back gate forms another knob for depleting the dots.

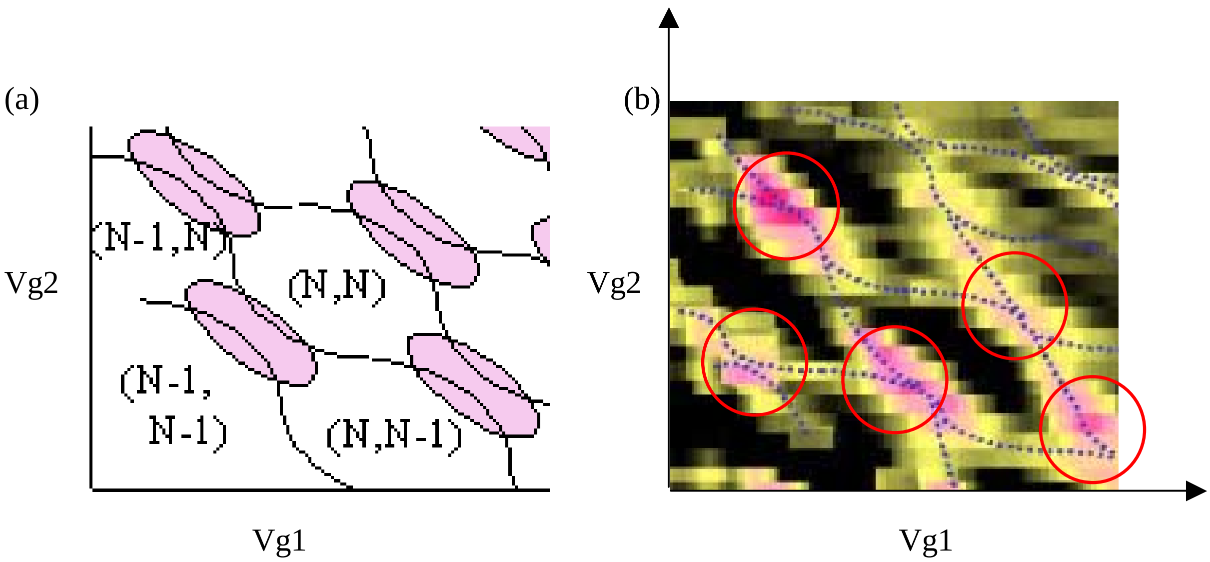

Figure 2. (a) Schematic charge diagram as a function of the two side gate voltages. The solid lines enclose regions of constant charge configuration. The circled areas indicate the regions of current resonances (triple points) (b) Experimental charge diagram in the plane of two side gate voltages (Vg1 and Vg2) The circled areas again indicate triple point regions.

References:

[1] D. Loss and D.P. DiVincenzo, Phys. Rev. A **57**, 120 (1998).
[2] G. Burkard, PhD. Thesis, Universität Basel (2001).
[3] G. Burkard, D. Loss, and D.P. DiVincenzo, Phys. Rev. B **59**, 2070 (1999).
[4] W.G. van der Wiel *et al*., Rev. Mod. Phys. **75**, 1 (2003).