Electrical Manipulation of Electron and Hole Spins in Si Qubits

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We review our recent results on the modeling of the electrical manipulation of electron and hole spins in silicon quantum dots. We focus on silicon-on-insulator (SOI) devices as an illustration (Fig. 1). Fast Rabi oscillations (up to 80 MHz) have indeed been measured in hole spin qubits [1], and Electric Dipole Spin Resonance (EDSR) has been demonstrated in electron devices despite the weak spin-orbit coupling (SOC) [2]. These devices are modeled with multi-bands **k.p** (holes) or tight-binding methods (electrons) (Fig. 2). The latter indeed account for valley and spin-orbit physics in the conduction band at the atomic scale. As for electrons, the calculations show that the coupling between spins and electric fields results from a subtle interplay between spin-orbit and valley interactions [2]. When the up spins of one valley anti-cross the down spins of the other, they get mixed by SOC, allowing for electrically driven spin transitions (Fig. 4). We argue, in particular, that SOC is enhanced by the very low symmetry of the "corner dots" formed in SOI devices (Fig. 3). We demonstrate that the valley splitting and the SOC can be tailored by front and back-gate electric fields; and we propose a manipulation scheme where an almost pure spin qubit (well protected from charge noise but hardly controllable electrically) can be transformed back and forth into a spin-valley qubit (or even a pure valley qubit) for fast electrical manipulation [3]. The physics of holes is very different. We show that the Rabi oscillations of holes are usually driven by a complex interplay between the motion of the dot as a whole in the electric field of the gate and the mixing of higher-lying excitations into the qubit states by the anharmonic components of the potential. These mechanisms can be described in a unified framework based on a gyromagnetic g-matrix and on its derivative with respect to the gate voltage [1, 4]. This g-matrix formalism can be used to model spin qubits at a very low computational cost (Fig. 5). As an illustration, we discuss the role of strains in spin qubits and show that silicon provides the best opportunities for fast hole spin Rabi oscillations owing to its very anisotropic valence band. This work was supported by the French ANR project MAQSi and the EU H2020 project MOSQUITO.

[1] A. Crippa *et al*., Physical Review Letters **120**, 137702 (2018).
[2] A. Corna *et al*., npj Quantum Information **4**, 6 (2018).
[3] L. Bourdet and Y.-M. Niquet, Physical Review B **97**, 155433 (2018).
[4] B. Venitucci *et al*., Physical Review B **98**, 155319 (2018).

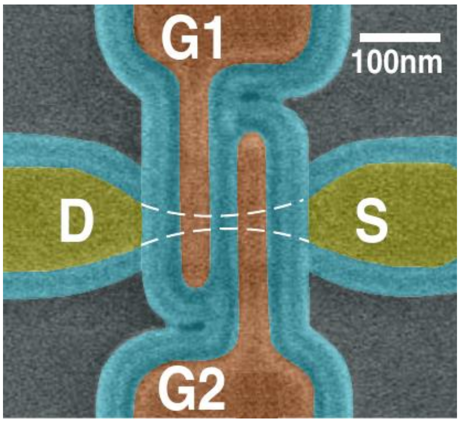

Fig.1: SEM image of a SOI device. The gates G1 and G2 control two quantum dots along a [110] Si nanowire outlined by the dashed white lines. The dot under G1 is used as a filter to measure the spin in the qubit under G2 through Pauli spin blockade of the source-drain (SD) current. The qubit is manipulated by radio-frequency pulses on G2 [1].

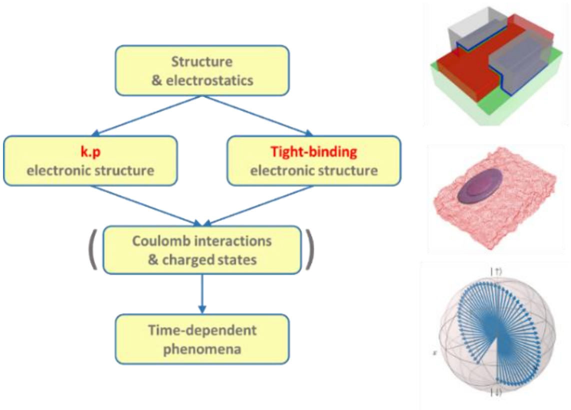

Fig. 2: Computational methodology developed for the qubits.

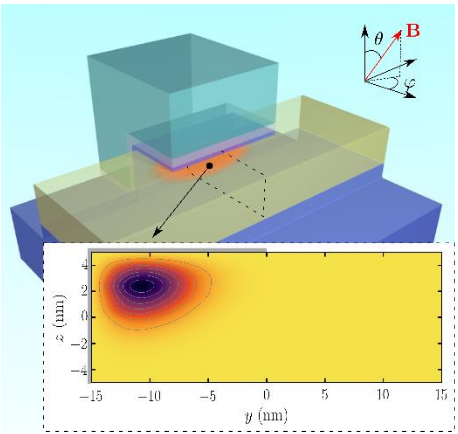

*Fig. 3: 3D model of a SOI device with a Si nanowire in yellow, SiO_2 in dark blue, and a partly overlapping gate in light blue. The location of the electron trapped under the gate is sketched in orange. A map of the squared wave function is plotted in the cross-section outlined by the dashed black lines. The orientation of the magnetic field **B** (see Fig. 5) is characterized by the angles θ and φ.*

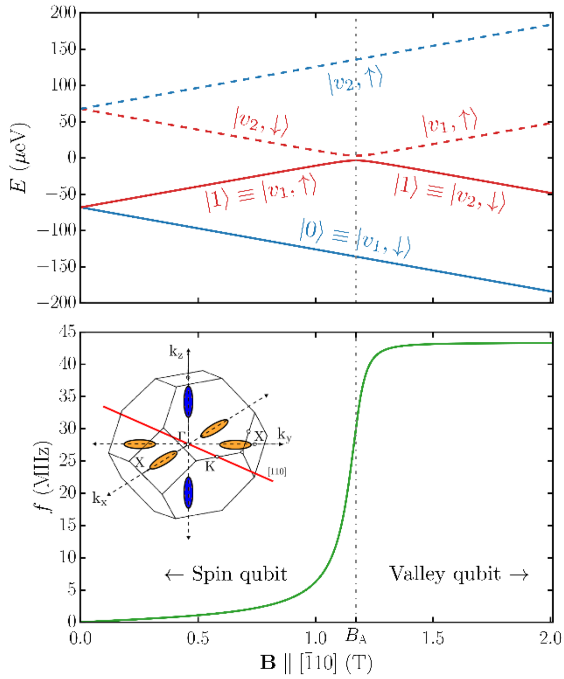

Fig. 4: (top panel) Single-particle energy levels in the conduction band of a thin Si quantum dot as a function of the magnetic field. At zero field, the degeneracy between the ±Z valleys is lifted by steep confinement at the Si/SiO_2 interface; the resulting v_1 and v_2 states are further split by the Zeeman interaction at finite magnetic field. The $|v_1,\uparrow\rangle$ state anti-crosses the $|v_2,\downarrow\rangle$ state around $B = B_A$ due to SOC; This enables electrically-driven Rabi oscillations between the lowest two states $|0\rangle$ and $|1\rangle$ as the dipole matrix element between $|v_1,\downarrow\rangle$ and $|v_2,\downarrow\rangle$ is finite. The calculated Rabi frequency is plotted in the lower panel [2, 3].

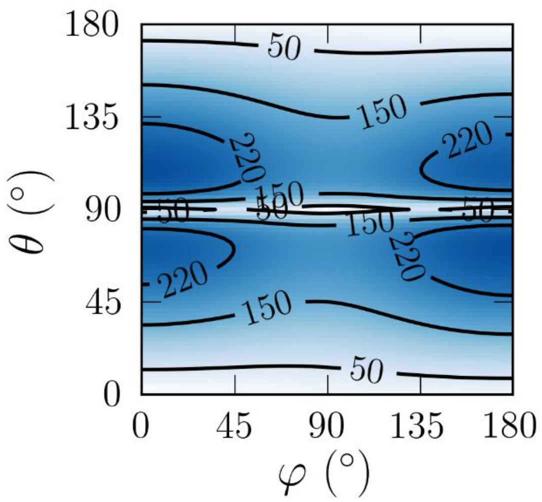

Fig. 5: Map of the Rabi frequency (MHz) of a heavy-hole spin qubit as a function of the orientation of the magnetic field, characterized by the angles θ and φ (see definition on Fig. 3) [4].