

Electrical control of a long-lived spin qubit in a Si/SiGe Quantum Dot.

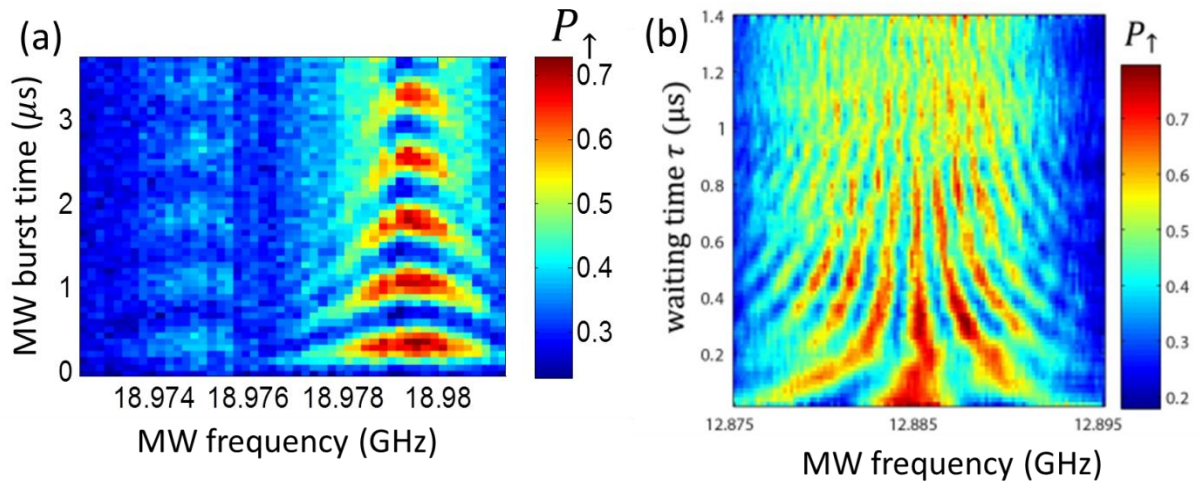


Fig. (a) Measured spin-up probability as a function of MW frequency and burst time. (b) Measured spin-up probability as a function of MW frequency and waiting time τ between two $\pi/2$ (75 ns) pulses with equal phase, showing Ramsey interference.

Electron spins in Si/SiGe quantum dots are one of the most promising candidates for a quantum bit for their potential to scale up and their long dephasing time. We realized coherent control of single electron spin confined in a single quantum dot (QD) defined in a Si/SiGe 2D electron gas [1]. Spin rotations are achieved by applying microwave excitation to one of the gates, which oscillates the electron wave function back and forth in the gradient field produced by cobalt micromagnets fabricated near the dot. The electron spin is read out in single-shot mode via spin-to-charge conversion and a QD charge sensor.

In earlier work [1], both the fidelity of single-spin rotations and the spin echo decay time were limited by a small splitting of the lowest two valleys. By changing the direction and magnitude of the external magnetic field as well as the gate voltages that define the dot potential, we were able to increase the valley splitting and also the difference in Zeeman splittings associated with these two valleys. This has resulted in considerable improvements in the gate fidelity and spin echo decay times. Thanks to the long intrinsic dephasing time $T2^* = 950$ ns and Rabi frequency of 1.4 MHz, we estimated (via randomized benchmarking) an average single qubit gate fidelity of an electron spin in a Si/SiGe quantum dot of $\sim 99\%$. The dephasing time is extended to ~ 70 μs for the Hahn echo and up to ~ 400 μs with CPMG128.

In parallel, the presence of the excited valley-orbit state, close in energy and strongly coupled to the ground state, introduces a substantial non-linearity in our system [2]. This non-linearity allows us to also achieve coherent single-spin control by second harmonic generation, which means we can drive an electron spin at half its Larmor frequency. As expected, the Rabi frequency depends quadratically on the driving amplitude and the periodicity with respect to the phase of the drive is twice that of the fundamental harmonic. The maximum Rabi frequency for the second harmonic is just a factor of two lower than that achieved for the first harmonic. Furthermore, combined with the lower demands on microwave circuitry when operating at half the qubit frequency, our observations indicate that second harmonic driving can be a useful technique for future quantum computation architectures.

Finally, we also observe a transition whereby both the spin and the valley state are flipped at the same time. We clearly demonstrate how both externally electric fields and electrical noise dramatically influence the frequency of this inter-valley spin resonance transition, dominating its coherence properties. In fact the estimated upper bound for the $T2^*$ of the inter-valley spin resonance is around

100 ns, almost 10 times lower than the coherence time reported above for the intra-valley spin resonances. We ascribe these observations to the non-vanishing dipole matrix elements between valley states coming from valley-orbit coupling in the presence of interface roughness [3].

Altogether, these measurements have significantly increased our understanding of the spin and valley physics in Si/SiGe and raised the prospects of spin qubits in Si/SiGe quantum dots.

1. E. Kawakami*, P. Scarlino* et al., Nature Nanotechnology 9, 666-670 (2014).
2. P. Scarlino et al., arxiv:1504.06436 (PRL, in press).
3. Gamble et al., Phys. Rev. B 88, 035310 (2013).