Exploiting the non-Abelian Berry phase for coherent control of spin qubits in semiconductors

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Spin qubit arrays based on semiconductor quantum dots are promising candidates for quantum computing, due to their small footprint, potential for scalability and few-Kelvin operation, as well as high-fidelity quantum logic and readout. Traditionally, spin qubits are operated in a finite magnetic field, using resonant qubit control with microwaves. Operating spin qubits at zero magnetic field has not been demonstrated yet, but it is expected to yield interesting advantages, such as an increased coherence time, and major technological simplifications, e.g., alleviating the need for a high-field magnet, microwave sources, coax lines, etc.

At zero magnetic field, a spin qubit has no energy splitting, hence new techniques substituting traditional resonant control must be devised [1,2]. A key result of this work is that we theoretically demonstrate that the non-Abelian Berry phase (NABP) induced by spin-orbit interaction in state-of-the-art quantum dot array devices can be used to realize single-qubit gates at zero magnetic field, by adiabatically shuttling a single carrier through a loop of quantum dots [3].

We also identify fingerprints of the NABP in spin control experiments carried out at finite magnetic field [4,7]. In particular, we show that the theory of g-tensor modulation, often used to describe electrically driven spin resonance, has to be supplemented by a geometrical term corresponding to the NABP, to describe spin dynamics induced by two simultaneously driven gate electrodes [4]. This is true not only for monochromatic driving, but also for the bichromatic resonance we have proposed [5], and we have demonstrated recently [6] in collaboration with TU Delft. We derive the formulas describing the parameter dependence of the Rabi frequency and the Bloch-Siegert shift for both cases [4], providing key tools for the quantitative analysis of experiments. We also identify a novel spin resonance mechanism at finite magnetic field that is also a consequence of the NABP [7].

Our results [3,4,5,6,7] pave the way to design and understand experiments where spin qubit dynamics in semiconductor quantum dots is governed by the NABP induced by spin-orbit coupling. State-of-the-art planar silicon and germanium devices with hole carriers are particularly well suited for such experiments, due to their strong spin-orbit interaction and high material quality. The experiments we propose for finite magnetic field are straightforward to implement with existing devices, and would constitute a major step towards spin qubit operation at zero magnetic field, potentially enabling holonomic quantum computing [8] with spin qubits.

References

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