High Quality Qubit Operations in Semiconductor Quantum Dots

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Abstract

Achieving useful quantum computation (QC) is a goal that presents physical science with a diverse set of difficult challenges. Quantum bit (qubit) operations have been demonstrated in trapped-ion and nuclear-magnetic-resonance systems but there is no apparent strategy that could scale these systems to functional sizes, motivating a search for alternatives in the solid state. Solid state qubits, however, typically involve a macroscopic number of atoms (10^4 or more), making it difficult to achieve the necessary isolation of the quantum degrees of freedom intended for qubit manipulation. The degree of quantum coherence of a two-level system is partially specified by the quality factor Q_o = D / T_2 / h where D is the level spacing and T_2 the coherence time. Q_o/2π corresponds to the number of free turns that a pseudospin can perform in a coherence time. Since QC requires active manipulation of qubits, however, the Rabi rotation quality factor, Q_R = Ω / T_2 / h where Ω is the Rabi frequency, is equally important.

We report on a new milestone in the achievement of large Rabi rotation quality factor Q_R in semiconductor quantum dots (SQDs). Unlike superconductor qubits for which the connection to the outside world is always present through the biasing circuitry, exciton based qubits in semiconductor quantum dots (SQDs) share with NMR and trapped ion systems the advantage that the controlling laser pulses can be turned on and off as needed. Furthermore, the possibility of incorporating photonic crystal technology enhances prospects for large scale integration. However, although ROs have been demonstrated in these systems previously, the number of visible oscillations was very low, only ~ 2π. Also, as reported by Stievater et al., increasing Ω led to a deterioration of Q_R because Γ = h / T_2 was found to be proportional to Ω^2. This apparent low quality of excitonic qubits has stimulated the proposal of alternate SQD based schemes, for example the use of trion – based qubits for which T_2 is a spin coherence time which can be much longer. In this report, we demonstrate that the apparent low quality of exciton qubits is not universal. By using self-assembled QDs (SAQDs) which have electronic degrees of freedom that are better isolated, we show that exciton qubits can have excellent quality factors. In particular, we demonstrate (a) free rotation quality Q_o ~ 10^5, and (b) 10π ROs with Q_R ~ 20. Moreover, we found a linear dependence of Γ upon Ω, thus maintaining the same Q_R value even at higher manipulation rate. Finally, we found that the extra damping of coherence during Rabi oscillations is primarily due to the excitation of other QDs in the ensemble at high laser intensity (a decoherence source that can be mitigated by performing the excitation locally and reducing the QD density). Since we used only the exciton excited states whose coherent time is a factor of 20 smaller than that of the exciton ground states, we conclude that when the exciton ground state is used, all figure of merits will increase by at least 20 fold. Furthermore, there exists a clear strategy to further reduce the excitation of other QDs during the ROs, suggesting a route which can raise both coherence factors to the range ~ 10^4 required for practical utility.