Flopping-mode electric dipole spin resonance

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(Received 6 May 2019; revised manuscript received 25 November 2019; published 8 January 2020)

Traditional approaches to controlling single spins in quantum dots require the generation of large electromagnetic fields to drive many Rabi oscillations within the spin coherence time. We demonstrate “flopping-mode” electric dipole spin resonance, where an electron is electrically driven in a Si/SiGe double quantum dot in the presence of a large magnetic field gradient. At zero detuning, charge delocalization across the double quantum dot enhances coupling to the drive field and enables low-power electric dipole spin resonance. Through dispersive measurements of the single-electron spin state, we demonstrate a nearly three order of magnitude improvement in driving efficiency using flopping-mode resonance, which should facilitate low-power spin control in quantum dot arrays.

DOI: 10.1103/PhysRevResearch.2.012006

Recent advances in silicon spin qubits have bolstered their standing as a platform for scalable quantum information processing. As single-qubit gate fidelities exceed 99.9% [1], two-qubit gate fidelities improve [2–6], and the field accelerates towards large multiqubit arrays [7,8], developing the tools necessary for efficient and scalable spin control is critical [9]. While it is possible to implement single-electron spin resonance in quantum dots (QDs) using ac magnetic fields [10], the requisite high drive powers and associated heat loads are technically challenging and place limitations on attainable Rabi frequencies [11]. As spin systems are scaled beyond a few qubits, methods of spin control which minimize dissipation and reduce qubit crosstalk will be important for low-temperature quantum information processing [12].

Electric dipole spin resonance (EDSR) is an alternative to conventional electron spin resonance. In EDSR, static gradient magnetic fields and oscillating electric fields are used to drive spin rotations [13]. The origin of the effective magnetic field gradient varies across implementations: intrinsic spin-orbit coupling [14–16], hyperfine coupling [17], and g-factor modulation [18] have been used to couple electric fields to spin states. The inhomogeneous magnetic field generated by a micromagnet [19,20] has been used to create a synthetic spin-orbit field for EDSR, enabling high-fidelity control [1]. Conveniently, this magnetic field gradient gives rise to a spatially varying Zeeman splitting, enabling spins in neighboring QDs to be selectively addressed [11,19,21–25].

In this Rapid Communication, we demonstrate a mechanism for driving low-power, coherent spin rotations, which we call “flopping-mode EDSR.” In conventional EDSR, the electric drive field couples to a charge trapped in a single quantum dot, leading to a relatively small electronic displacement [16]. We instead drive single spin rotations in a DQD close to zero detuning,  $\epsilon = 0$, where the electric field can force the electron to flop back and forth between the left and right dots in the “flopping mode,” thereby sampling a larger variation in transverse magnetic field.

Neglecting spin, the Hamiltonian describing a single-electron DQD is $H_0 = (\epsilon/2) \tau_z + t_c \tau_x$, where $t_c$ is the interdot tunnel coupling and $\tau_x$ are the Pauli operators in position $(L, R)$ space [26]. In the highly detuned regime of a DQD (with $|\epsilon| \gg t_c$), the electron is strongly localized in either the left $|L\rangle$ or right $|R\rangle$ dot with orbital energy $E_{\text{orb}} \approx 3$ meV [27]. When $\epsilon = 0$ the charge delocalizes across the DQD, leading to the formation of bonding and antibonding states $|\mp\rangle = (|L\rangle \mp |R\rangle)/\sqrt{2}$. Here, the bonding-antibonding energy difference $2t_c \approx 20–40$ $\mu$eV is dominant and the charge is much more susceptible to oscillating electric fields [28,29].

The application of a magnetic field results in Zeeman splitting of the spin states. When the Zeeman energy and $2t_c$ are comparable, the combination of a magnetic field gradient and the large electric dipole moment results in strong spin-charge hybridization. This allows electric fields to couple to spin indirectly via the charge [30–32]. We coherently manipulate a single-electron spin qubit in the flopping-mode regime and find that the power required to drive Rabi oscillations is almost three orders of magnitude less than in single dot EDSR. Additionally, we find a “sweet spot” at $\epsilon = 0$ where charge noise is suppressed [33], leading to a fourfold improvement in the qubit quality factor.

The device consists of two single-electron natural-Si/SiGe DQDs (DQD1 and DQD2) that are embedded in a half-wavelength Nb superconducting cavity with resonance

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The EDSR mechanism is most effective near $\epsilon = 0$, where the electric dipole moment $p$ is largest [Fig. 1(c)].
FIG. 2. (a) Phase response of the cavity transmission $\Delta \phi$ as a function of $B^{\text{ext}}$ and $\epsilon$ for DQD1 with $2\tau_s / h = 7.4$ GHz. Dashed lines show asymmetry in spin-cavity interactions at high and low detuning. The extracted $\Delta B^{\text{ext}}$ is used to determine $b_z$. (b) Difference between the cavity frequency $f_c$ and spin transition frequency $f_{s0}$ as a function of $\epsilon$ for $B^{\text{ext}} = 91.9$ mT (blue) and $B^{\text{ext}} = 91.5$ mT (purple). Inset: Cartoon of a DQD in the presence of spatially varying $B^{\text{ext}} (B^{\text{mic}})$ fields, not drawn to scale. (c) $f_{s0}$ as a function of $\epsilon$ for DQD1, with $2\tau_s / h = 11.1$ GHz, as extracted from time-domain Rabi oscillations. The dashed line shows a fit to theory with $2\tau_s / h = 11.1$ GHz, $B_z = 209.4$ mT, $b_z = 15$ mT, and $b_c = 0.27$ mT.

The funnel-shaped feature in Fig. 2(a) is a consequence of detuning-dependent charge hybridization and Zeeman physics [32,36] in the regime where $E_{01} \ll 2\epsilon_c$. At low $B^{\text{ext}}$, the spin transition is detuned from the cavity, but there is still a small phase response around $\epsilon = 0$ due to the large electric dipole moment [34,35]. At large detunings ($|\epsilon| \gg 2\epsilon_c$) the energy splitting $E_{01}$ is dominated by Zeeman physics. At small detunings, levels $|1\rangle$ and $|2\rangle$ hybridize due to transverse magnetic fields [36], which pulls $E_{01}$ slightly below the Zeeman energy. As a result, when $E_{01}$ is slightly less than $hf_c$ at $\epsilon = 0$, there are two values of finite detuning for which $E_{01}$ is on resonance with the cavity, giving rise to the wings of the funnel-shaped feature that begins at $B^{\text{ext}} \sim 91.2$ mT. As $B^{\text{ext}}$ increases further the values of detuning that lead to resonance with the cavity shift closer to $\epsilon = 0$. Eventually, at $B^{\text{ext}} \sim 91.9$ mT, the two resonance conditions merge at $\epsilon = 0$. Figure 2(b) shows theoretical predictions for $f_c - f_{01}$ as a function of $\epsilon$ for $B^{\text{ext}} = 91.5$ and 91.9 mT, with $f_{01} \equiv E_{01}/h$.

With the electron spin resonance frequency $f_{01}$ now mapped out as a function of $B^{\text{ext}}$ and $\epsilon$, we can drive coherent single spin rotations using flopping-mode EDSR. At $\epsilon = 0$, a microwave burst of frequency $f_s$ and duration $\tau_B$ is applied to gate P1 to drive coherent spin rotations. The final spin state is read out dispersively at $\epsilon = 0$ by measuring the cavity phase response $\Delta \phi$ [31].

The spin transition frequency $f_{01}$ is extracted from the center frequency of Rabi chevron data, and plotted in Fig. 2(c) as a function of $\epsilon$. When $2\tau_s \gg \tau_c$, the lowest $f_{01}$ occurs near $\epsilon = 0$ due to spin-charge hybridization, and $f_{01}$ increases as $|\epsilon|$ increases. The trends in these data are in general agreement with the data measured using microwave spectroscopy in Fig. 2(a). The asymmetry of the data in Figs. 2(a) and 2(c) about $\epsilon = 0$ is due to the longitudinal gradient field $b_z$. The difference in external field $\Delta B^{\text{ext}}$ [given by the splitting of the dashed lines in Fig. 2(a)] required to bring the spin onto resonance with the cavity at large negative and positive detunings provides a measure of $b_z$. From the data, we find that $\Delta B^{\text{ext}} = 0.34$ mT, and using the expression $2b_z = (1 + \chi)k^{\text{ext}}$, where $\chi$ is the micromagnet magnetic susceptibility [31], we extract $b_z = 0.27$ mT. We take the extracted value of $b_z$ and fit the data in Fig. 2(c), finding good agreement between experiment and our theoretical model.

Having gained a quantitative understanding of how $f_{01}$ depends on $\epsilon$, we now compare EDSR in the flopping-mode and single dot regimes. A typical flopping-mode data set is shown in Fig. 3(a), where $\Delta \phi$ is plotted as a function of $f_s$ and $\tau_B$. As expected, the Rabi oscillation visibility is maximal when $f_s$ is resonant with $f_{01}$. By simultaneously applying a microwave burst and square pulse to gate P1, we can drive coherent spin rotations at a value of detuning set by the amplitude of the square pulse. Due to the ratio of electric dipole moments in these regimes, the power $P$ required to drive fast coherent rotations in the single dot regime is expected to be much higher. As shown in the upper panel of Fig. 3(b), at $\epsilon = 0$ a Rabi frequency $f_{\text{Rabi}} \approx 6$ MHz is achieved with $P = -90$ dBm at the device. In contrast, when $\epsilon = -52$ $\mu$eV a power of $P = -83$ dBm is required to achieve approximately the same Rabi frequency [see Fig. 3(b), lower panel]. Power adjustments are implemented manually.
The actual power at the gate is determined by measuring the
imbepenence of detuning, a Rabi chevron is acquired with
f_\text{Rabi} \approx 6 \text{ MHz}, similar to Fig. 3(a). We take a Fourier trans-
f of each column of the chevron and identify f_\text{f01}. At this
f_\text{f01}, we fit the Rabi oscillations as a function of \tau_B to extract
T_2^{\text{Rabi}} and f_\text{Rabi}.

The Rabi frequency and Q factor are plotted as a function of 
\epsilon in Fig. 4(b). At finite detuning Q \approx 4. We observe more
than a fourfold increase in the quality factor, with Q = 18 at
\epsilon = 0. The enhancement of Q in the flopping-mode regime
can be attributed to the presence of the charge noise sweet spot, 
which to first order decouples the spin from electrical
detuning noise. While the Q factors achieved here are lower
than those reported elsewhere [1,5], from theoretical models
[37] we expect that for an optimized \tau_c, fabricating devices
on enriched \text{^{28}Si} quantum wells and reducing charge noise 
will yield quality factors comparable to those cited for con-
tentional EDSR [1]. Similar to other work [1], we observe a
deterioration in Q at high drive powers.

In summary, we demonstrate an efficient flopping-mode mecha-
nism for EDSR in semiconductor DQDs. Compared to single
dot EDSR, flopping-mode EDSR requires nearly
three orders of magnitude less power, rendering it a valuable
control technique for future spin-based quantum processors.
Conveniently, the flopping-mode regime of maximal power
efficiency coincides with a charge noise sweet spot, yield-
ing a fourfold improvement in qubit quality factor. While
the device studied here is embedded in a microwave cavity,
flopping-mode EDSR could be implemented in DQDs that are
read out using conventional spin-to-charge conversion [39] 
or Pauli blockade [40]. We anticipate that flopping-mode spin 
resonance will enable power-efficient single-qubit control in
large-scale silicon quantum processors.

This research was sponsored by ARO Grant No. W911NF-
15-1-0149 and the Gordon and Betty Moore Foundation’s
EPiQS Initiative through Grant No. GBMF4553. Devices 
were fabricated in the Princeton University Quantum Device
Nanofabrication Laboratory.

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