Quantum interferometry with a high-temperature single-spin qubit

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We study quantum interference effects of a qubit whose energy levels are continuously modulated. The qubit is formed by an impurity electron spin in a Si tunneling field-effect transistor, and it is read out by spin blockade in a double-dot configuration. The qubit energy levels are modulated via its gate-voltage-dependent g-factors, with either rectangular, sinusoidal, or ramp radio-frequency waves. The energy-modulated qubit is probed by the electron spin resonance. Our results demonstrate the potential of spin qubit interferometry that is implemented in a Si device and is operated at a relatively high temperature.

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Introduction.—Sensitive measurement techniques are based on the interference of waves. The most striking illustration is the recent use of interferometry for the detection of gravitational waves [1]. If in place of classical electromagnetic waves one can use the wave functions of quantum objects, such techniques can be called quantum interferometry. This was studied not only for conventional small quantum objects [2, 3], but also for large organic molecules [4, 5] and micrometer-size superconducting circuits [6–8]; see also a recent review article [9] for different realizations and applications in quantum sensing. Since it is difficult to maintain a coherent superposition of charge states, it might be more beneficial to use instead the spin degree of freedom [10]. Interestingly, silicon, the second most abundant element in the Earth’s crust and the base of modern electronics, is an ideal environment for spins in the solid state [11]. In this work, we will explore how to use a single-spin silicon-based qubit for quantum interferometry.

Among other characteristics, for quantum engineering it is important to have qubits which are “hot, dense, and coherent” [12]. In this context, “hot” means working in the technologically less challenging few-Kelvin regime rather than being cooled down to the milli-Kelvin domain. “Dense” refers to the possibility to achieve high density of quantum dots or donors in semiconductors. Another benefit of this platform is the compatibility with the well-developed complementary-metal-oxide-semiconductor (CMOS) technology. Even more, it has been shown [13–15] that transistors can behave as quantum dots, in which either charge or spin qubits are realized.

While usually quantum systems are driven by sinusoidal signals, it is also possible to drive them by square-wave signals. This allows one to rapidly move a qubit from one state to another, which we can refer to as latching modulation of qubit states [16, 17]. If this is done with a periodicity shorter than the coherence time, then in the response there are two separate peaks situated at the two resonance frequencies corresponding to the two states. Increasing the modulation frequency, the coherent response is displayed as an averaged signal, situated at a frequency between the two resonance frequencies mentioned above, which is known as motional narrowing. Both motional averaging and narrowing are known in NMR systems and recently studied in superconducting systems [18, 19]. In this way, by changing the modulation frequency, namely its ratio to the coherence rate, one can observe the transition between classical (incoherent) and quantum (coherent) regimes, as in Refs. [18, 20–22].

In this work, we focus on a single spin 1/2 qubit and study the effect of continuous modulation of the qubit energy. In this way, we explore the motional averaging not only for the symmetric latching modulation (which was previously demonstrated in superconducting qubits [16–18]), but also in the asymmetric regime, where dwelling in one state is longer than in the other state. A square-wave modulation with variable duty ratio shows weighted motional averaging. At low modulation frequency, this is visualized, in the frequency dependence, by two peaks (with weighted height and width), while at high modulation frequency there is only one averaged peak. We also demonstrate the sinusoidal energy modulation of the spin qubit and show the Landau-Zener-Stückelberg-Majorana (LZSM) interference of the spin resonance signal. This is the first demonstration of LZSM interference where the temperature is much higher than the photon energy of the sinusoidal modulation frequency. For realizations of the low-temperature LZSM interference in quantum-dot
systems see Refs. [23–30].

Device and measurement.—We used a spin qubit device based on a short-channel tunneling field-effect transistor, TFET, with the implanted deep impurity, Fig. 1(a) [31–35]. The device is essentially a gate-tunable PIN diode (a diode with an undoped intrinsic semiconductor region between a p-type semiconductor and an n-type semiconductor region). For an appropriate channel length, a three-step tunneling from the n-type source electrode to the p-type drain electrode occurs via two localized states in the channel, Fig. 1(b). The PIN structure allows tunneling via the localized states of a deep impurity and a shallow impurity [35, 36].

Spin blockade and ESR.—The device has two localized states, which behave as a double quantum dot device, where the current is defined by single-electron transport [37]. Under an appropriate source voltage $V_{SD}$ and gate voltage $V_G$, the device shows spin blockade (SB) [38]. At the electron spin resonance (ESR) for one of the spins in the double dot, the source-drain current $I_{SD}$ increases due to the lifting of the spin blockade Fig. 1(c) [13, 39]. Note that the large on-site Coulomb energy and strong confinement of these impurities allow spin-qubit operation at relatively high temperatures and low magnetic fields. Two ESR transitions with $g$-factors $g = 2.3$ and $g = 2.7$ for the two impurities are observed. Hereafter, we only focus on the ESR peaks at $g = 2.3$.

Tuning the $g$-factor by the gate voltage.—Figure 2(a) shows the ESR peak observed in the spin-blockade regime. The ESR linewidth, i.e. the inverse of the coherence time $T_2^*$, is reasonably limited by the spin blockade lifetime as well as natural abundance of $^{29}$Si [40]. Changing the gate voltage $V_G$ within the spin blockade region changes the $g$-factor by about 1% due to the Stark effect [Fig. 2(b)] [41]. Therefore, the device behaves as a spin qubit. We describe this as a doubly-driven two-level system with the pseudo-spin Hamiltonian

$$H(t) = B_z(t)\sigma_z/2 + B_x(t)\sigma_x/2.$$  

(1)

The longitudinal part is defined by the Zeeman splitting, $B_z(t) = g(t)\mu_B B$. The time-dependent gate voltage changes the $g$-factor by a small value and we have $B_z/B = \omega_0 + \delta \cdot s(t)$, where the amplitude $\delta \ll \omega_0$; $\omega_0 = 2\pi f_0$ represents the ESR frequency. In this work, we consider three types of signals [36]: the sinusoidal modulation, $s(t) = \cos(\Omega t)$, the latching modulation, given by

$$s(t) = \begin{cases} 2(1 - d), & 0 < \Omega t/2\pi < d, \\ -2d, & d < \Omega t/2\pi < 1, \end{cases}$$  

(2)

where $d$ is the duty-cycle ratio, and the ramp modulation, given by the fractional part in $\{\Omega t/2\pi\}$. Note that for a symmetric latching modulation, with $d = 1/2$, from Eq. (2), we have $s(t) = \text{sgn}(\cos(\Omega t))$. In addition, the transverse part of the Hamiltonian is defined by the MW voltage applied to the substrate, $B_x/B = 2G\cos(\omega t)$ with amplitude $G$ and circular frequency $\omega = 2\pi f$. The modulation is assumed to be slow, i.e. $\Omega \ll \omega$.

Square-wave modulation.—In figures 3 and 4 we present the results of our measurements and calculations for symmetric and asymmetric square-wave modulation signals. The left panel focuses on the source-drain current $I_{SD}$, showing the current derivative, $dI_{SD}/df$, in its main panel. The right panel presents the corresponding theoretical predictions for the qubit upper-level occupation.

By adding a square-wave MHz modulation signal to the gate [Fig. 3(a)], the gate voltage, i.e. $g$-factor, can be switched between two values, as described by Eq. (2). Figure 3(d) shows $I_{SD}$ at $V_G = -0.36$ V and square wave of frequency 0.5 MHz and amplitude 32 mV. Due to the slow measurement with a time constant (that shows how fast the measured current changes) $\sim 0.3$ s, we observe the two ESR peaks with two different $g$-factors for $V_G = -0.36 + 0.016$ V and $-0.36 - 0.016$ V, respectively. By increasing the modulation frequency, the ESR peaks show a characteristic interference pattern and eventually a strong (main) peak appears with weak sideband peaks [Fig. 3(b)]. The characteristic crossover of the modulation frequency appears around $(T_2^*)^{-1}$. The strong single peak at $f = f_0 = 9.01$ GHz [Fig. 3(b)] is a result of motional averaging of the two peaks for the slow modulation [Fig. 3(d)]. A similar pattern was observed for latching modulation of the energy of a superconducting qubit in Ref. [16]. Changing the modulation amplitude shows a similar behavior with similar crossover frequency [36].

In order to describe the system, we solve the Bloch equations with the above Hamiltonian. We assume that $\omega \gg \Omega$ and after a rotating-wave approximation

$$H_1 = \frac{\hbar}{2} [\Delta\omega + \delta \cdot s(t)] \sigma_z + \frac{\hbar G}{2}\sigma_x,$$

(3)

where $\Delta\omega = \omega_0 - \omega = 2\pi (f_0 - f)$. Details of the calculations are presented in [36], cf. Ref. [42]. As a result, the upper-level occupation probability is readily obtained from the stationary solution of the Bloch equations:

$$P_x(\Delta\omega, \frac{\delta}{\Omega}) = \frac{1}{2} \sum_{k=-\infty}^{\infty} G_k^2(\delta/\Omega) + \frac{\hbar}{2} \frac{G_k^2(\delta/\Omega)}{(\Delta\omega - k\Omega)^2 + \Gamma_1 \Gamma_2},$$

(4)

where $G_k(x) = G |\Delta_k(x)|$, which can be interpreted as the dressed qubit gap, modulated by the function $\Delta_k(x)$. The relaxation and decoherence rates are denoted as $\Gamma_1 = T_1^{-1}$ and $\Gamma_2 = T_2^{-1}$, respectively. In particular, for rectangular driving with duty-cycle ratio $d$, we obtain:

$$|\Delta_k(x)| = \frac{2}{\pi} \frac{x \sin [\pi d (k - 2 (1 - d)]}{(k + 2dx) (k - 2 (1 - d))}.$$  

(5)

We can interpret the effective Hamiltonian (3) as follows. The microwave drive dresses the two-level system resulting in an energy level difference $\Delta\omega$: when this is matched to the $k$-photon energy of the rf-signal, the dressed qubit is resonantly excited. Indeed, the upper-level population in Eq. (4) has maxima at $|\Delta\omega| = k\Omega$ [18, 43]. With Eqs. (4-5) with $d = 1/2$ we plot Fig. 3(b).
We have checked that the ones calculated analytically with these equations agree nicely with the ones calculated numerically.

**Asymmetric modulation.**—Changing the duty ratio $d$ (ratio of the high $V_G$ signal duration to the period; for the previous square wave the duty ratio was 50%), shows both asymmetric modulation and weighted motional average, as demonstrated in Fig. 4. Because the modulation voltage is added through the block capacitor, the areas of the signal curves below and above the average gate voltage $V_G$ are equal, as shown in Fig. 4(a). Figure 4(d) shows the ESR under slow modulation of the square-wave signal with a 20% duty ratio. The two ESR peak heights are different, reflecting the duty ratio. For fast modulation, the main peak appears at the weighted averaged frequency [Fig. 4(b)].

We repeat similar measurements with various duty ratios (from 20 to 80%). In figure 4(h) we plot the heights of the two ESR peaks at lowest modulation frequency. For each duty ratio, we also plot distances between the above two peak positions and the motional averaged main peak position at the highest modulation frequency [Fig. 4(i)]. Both of the peak heights and distances reflect the duty ratios. The ratio of the peak heights and the frequency distances are plotted in Fig. 4(j), and show the motional-averaged main peaks, which indeed appear at the weighted average frequency. The deviations from linear dependencies in these plots, especially for the duty ratio of 20%, are due to the gate-voltage dependence of the ESR peak height that is also seen in Fig. 2(b). More detailed measurements for each duty ratio are shown in [36].

We note here the following interesting features of the weighted motional averaging. The rectangular-pulse modulation places the qubit in one of the two allowed positions, and the low-frequency characteristics reflect the weighted time spent in those two states. For high $\Omega$, the principal ESR line is situated in-between the two qubit states, the position of which is independent of the duty ratio. A counter-intuitive aspect is that the position of the localized states (in a deep impurity and a shallow impurity) for a double quantum dot in which the spin qubit is formed in the spin-blockade regime. We demonstrated coherent control by modulating the qubit energy with various continuous waveforms. In particular, when driven by asymmetric rectangular pulses with duty ratio $d$, we observed interferograms, which we refer to as weighted motional averaging. At low frequency, this displays $d$-weighted peaks which, at higher frequency, merge into one peak. To conclude, we summarize the advantages of the silicon single-spin interferometers: they operate at relatively high temperature (1.6 K), the $g$-factor is controlled by the gate voltage ($\sim 1\%$, important for selectivity of measurements), the relaxation times $T_1, T_2$ are large, the fabrication is based on the well-developed techniques for silicon, such as CMOS, and they can be manipulated into the ESR and Pauli spin blockade regimes.

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FIG. 1: High-temperature TFET-based single-spin qubit. (a) Schematic of the device and measurement set up. The transistor is defined on a SOI structure with n-type source and p-type drain electrodes. The channel length and width are 80 nm and 10 µm, respectively. The source-drain current $I_{SD}$ of the device is measured for the source-drain voltage $V_{SD}$ and the gate voltage $V_G$ at temperature $T = 1.6$ K achieved with a pumped $^4$He cryostat. A magnetic field $B$ is directed along the source-drain current. A microwave (MW) signal is applied on the substrate. A gate-voltage modulation in the MHz regime is applied through a high-pass block capacitor with cutoff frequency ($< 10$ kHz) much smaller than the modulation frequency ($\sim$MHz). (b) Schematic of the potential landscape of the device. (c) Schematic of the single-electron tunneling cycle in the spin-blockade regime. Consider the initial situation in (i) with one electron in the right dot. The localized energy level on the left (closer to the n-type source electrode) is the electron-number $N = 1$ state of the deep impurity, while the right two energy levels are those of the $N = 1$ and $N = 2$ states (separated by the on-site Coulomb energy $E_C \sim 10$ meV) of the shallow impurity, respectively. The Fermi energy of the p-type electrode sits between the two right states with a thermal broadening $k_B T$. The tunneling cycle occurs following the dark gray arrows, with equal probabilities for the (i)$\rightarrow$(ii) and (i)$\rightarrow$(ii') trajectories, and eventually is blocked at the parallel-spin state (ii'). Under the ESR condition of the right spin, the spin blockade is lifted, as shown in the inset, and the source-drain current is increased due to the newly opened cycle, as indicated with the light gray arrows: (i)$\rightarrow$(ii')$\rightarrow$(iii')$\rightarrow$(iii)$\rightarrow$(i). Note that the spin qubit energy levels have the separation $\Delta E \sim 9$ GHz $\cdot \hbar$ at $B \sim 1$ T and the qubit transition is described as flipping of the spin at (ii')$\rightarrow$(iii').
FIG. 2: ESR for the single-spin qubit with tunable g-factor. (a) The source-drain current $I_{SD}$ of the device at $V_{SD} = 0.33$ V and $V_G = -0.36$ V as a function of the frequency $f$ for various magnetic field detunings $\Delta B$ from $B = 0.2755$ T, with fixed MW power of $-18$ dBm. ESR peaks with a linewidth of 4 MHz are observed. (b) $I_{SD}$ of the device at $V_{SD} = 0.33$ V and $B = 0.2755$ T versus the frequency $f$ for various gate voltage detuning $\Delta V_G$ away from $V_G = -0.36$ V. The g-factor (thus the qubit energy) is increased for more positive $\Delta V_G$. The change of the g-factor is found to be linearly dependent on $\Delta V_G$. For $|\Delta V_G| > 20$ mV, the ESR response is not observed, suggesting the $V_G$ is out of the SB region. Note that the ESR peak is superimposed on the background current, which is around 2.5 pA. Both in (a) and (b) all the upper curves are shifted vertically, for clarity.
FIG. 3: Square wave modulation of the spin qubit.
(a) Shape of the rf signal. (b,c,d) The source-drain current $I_{SD}$ of the device with a square modulation of its full amplitude 32 mV added to the gate at $V_G = -0.36$ V through the high-pass block capacitor. Other conditions are the same as in Fig. 1. In panel (c) we present the intensity plot of $dI_{SD}/df$ versus the frequency $f$ and the square-wave modulation frequency $\Omega$ (log scale from 0.5 to 50 MHz), showing the evolution from the two ESR peaks into the strong main ESR peak and weak sideband peaks. Note that the distance between the main and the sideband peaks (seen in the upper area $> 10$ MHz) is linear in the modulation frequency $\Omega$. Panels (b) and (d) present the source drain current $I_{SD}$ at modulation frequencies of 50 MHz and 5 MHz, respectively. (e,f,g) Calculation of the upper-state population of the qubit under square-wave modulation of its energy. For calculations, the following parameters were used for all the graphs: $G/2\pi = 1.1$ MHz, $\Gamma_1/2\pi = 0.2$ MHz, $\Gamma_2/2\pi = 1$ MHz, and also for the right panels (e-g) here: $\delta/2\pi = 24$ MHz.
FIG. 4: Weighted averaging for the spin qubit versus the duty ratio $d$. (a) Shape of a square wave with $d = 20\%$. (b-d) Similar plot of $I_{SD}$ as in Fig. 3(b-d) but with a square wave with a 20\% duty ratio, which corresponds to $d = 0.2$. The modulation frequency is changed from 0.25 to 25 MHz in a log scale. (e-g) Calculation of the qubit upper-state population under square-wave modulation ($d = 0.2$) of its energy. Besides the duty ratio, other parameters are the same as in Fig. 3(e-g). Note that the main weighted averaged peak appears again at $f = f_0$ (here $f_0 = 9.02$ GHz), independent of the duty ratio. (h) Duty ratio dependence of the ESR peak heights at $\Omega/2\pi = 0.25$ MHz for lower frequency, $\Delta I_L$, and higher frequency, $\Delta I_H$. The $\Delta I_L$ and $\Delta I_H$ for $d = 0.2$ are indicated in (d). (i) The duty-ratio dependence among three ESR peaks, i.e. the motional averaged main peak at $\Omega/2\pi = 25$ MHz (9.021 GHz), to the ESR peaks of lower/higher frequency at $\Omega/2\pi = 0.25$ MHz. The distances between the peaks, $\Delta f_L$ and $\Delta f_H$, are indicated in (e) for $d = 0.2$. (j) Duty-ratio dependence of the contrasts for the peak heights and distances.
FIG. 5: Sinusoidal and ramp modulation. (a) Shape of the rf sinusoidal signal. (b) Source-drain current $I_{SD}$ under sinusoidal modulation with amplitude 24 mV. Intensity plot of $dI_{SD}/df$ versus the frequency $f$ and the modulation frequency $\Omega$ (linear scale from 0 to 80 MHz). (c) Calculation of the upper-state population of the qubit under the sinusoidal modulation of its energy. The parameters are the same as for Fig. 3 besides the amplitude, which here is $\delta/2\pi = 30$ MHz. (d) Shape of the ramp wave signal. (e) Source-drain current $I_{SD}$ under the ramp modulation with amplitude 36 mV. Intensity plot of $dI_{SD}/df$ as a function of the frequency $f$ and the modulation frequency $\Omega$ (log scale from 0.25 to 25 MHz). (f) Calculation of the upper-state population of the qubit under ramp modulation of its energy. The parameters are the same as for Fig. 3 besides the amplitude, which here is $\delta/2\pi = 27$ MHz.
In this Supplemental Material we present details about both our experimental layout and our theoretical approach. Also we provide here additional data for interferograms with various modulating signals.

I. DEVICE DETAILS

The tunnel field-effect transistor (TFET) is a kind of metal-oxide-semiconductor field-effect transistor (MOSFET) that has an n-type source and a p-type drain electrodes, effectively working as a gated PIN diode (a diode with an undoped intrinsic semiconductor region between a p-type semiconductor and an n-type semiconductor region). Its channel, kept intrinsic for zero gate voltage $V_G$, can be tuned into p- or n-type for large enough positive or negative $V_G$. A TFET is tuned on by gate-induced reduction of the PIN junction thickness, enabling steeper switchings than MOSFET. Recently, it has been intensively studied as a future low-power transistor element for large-scale integration [1]. Enhancement of the on-current is achieved by introducing deep impurities in the (relatively long-channel) TFETs, and this enhancement is ascribed to deep-level assisted resonant tunneling in the PIN junction.

In order to electrically access a single deep impurity, and use its spin for a high-temperature qubit, we introduce deep impurities in a short-channel TFET. Tunneling transport through a deep impurity level as well as the gate tuning of the level are possible in short-channel TFET provided that the deep impurity is located appropriately in the channel. In contrast to a MOSFET, the impurity-electrode tunnel coupling can be in a reasonable range of the TFET for realistic channel lengths (several tens of nm), even when the deepest level is located in the middle of the band gap.

Our TFET-based devices are fabricated with a process compatible with those for standard MOSFETs. Starting from silicon-on-insulator wafers, n-type electrodes (followed by p-type electrodes) are defined by standard ion implantations of shallow donors (shallow acceptors). Then, we lay both Al and N by the ion implantations in the whole area including source, channel, and drain, and follow by appropriate heat treatment. This process is known to form coupled Al-N impurity pairs in Si [2–5]. We found this is crucial for introducing deep impurity levels to TFETs. Indeed, if we omit this process, no TFETs (including short-channel ones) show the quantum-dot-like transport as described below, but only conventional characteristics of TFETs. Finally, the gate electrodes are formed with standard high-k/metal gate technology.

Some of our devices show characteristics similar to a double dot, which is formed when two quantum dots are connected in series between source/drain electrodes. Measurements of Coulomb diamonds, Coulomb conductance peaks and their temperature dependence suggest the formation of multiple dots in the device, composed of a deep impurity with strong confinement ($> 0.1$ eV) and at least one satellite dot nearby the deep impurity with weaker confinement ($\sim 5$-10 meV). Electron spin resonance (ESR) is seen in $I_{SD}$ at certain areas of the plane ($V_{SD}, V_G$), due to the spin blockade which occurs in these regions. For the device used in the main text, we observed the ESR spectra with two resonant lines with $g$-factors equal to 2.3 and 2.7. The peak of the ESR with the $g$-factor 2.7 is weak. See Ref. [6] and its supplemental materials for further details.
II. THEORETICAL DESCRIPTION OF THE DRIVEN AND MODULATED SINGLE SPIN

A. Energy-level modulations

Consider a doubly-driven two-level system, described by the Hamiltonian

\[ H(t) = \frac{B_z(t)}{2} \sigma_z + \frac{B_x(t)}{2} \sigma_x \]  

(1)

with

\[ B_z(t)/\hbar = \omega_0 + \delta \cdot s(t), \]  

(2)

where we assume the amplitude to be small, i.e. \( \delta \ll \omega_0 \), and

\[ B_x(t)/\hbar = 2\cos \omega t, \]  

(3)

(Here the factor 2 is introduced so that the amplitude defines the Rabi frequency.)

For the longitudinal-field modulation, we consider different possibilities: (i) sinusoidal modulation, (ii) asymmetric latching modulation, and (iii) ramp modulation. Below we will discuss these regimes in more detail.

(i) The sinusoidal modulation is the one most often used, and it is given by

\[ s^{(i)}(t) = \cos \Omega t = \cos 2\pi \tau, \]  

(4)

where we introduced the dimensionless time

\[ \tau = \frac{\Omega t}{2\pi}. \]  

(5)

(ii) Next we consider a modulation with asymmetric rectangular pulses with duty ratio \( d \). This corresponds to a qubit latched in one of the two states, with fast switching between these states. We refer to this regime as “latching modulation” [7]. In this case we assume that the modulating function has two stages with equal areas under the curve:

\[ s_d^{(ii)}(\tau) = \begin{cases} 2(1-d), & 0 < \tau < d, \\ -2d, & d < \tau < 1. \end{cases} \]  

(6)

Here the factor 2 is introduced so that this modulating function changes between -1 and +1 for the symmetric 50% duty ratio:

\[ s_{0.5}^{(ii)}(\tau) = \begin{cases} 1, & 0 < \tau < 0.5, \\ -1, & 0.5 < \tau < 1. \end{cases} \]  

(7)

These two definitions can be written (with an insignificant shift of the time variable) as

\[ s_d^{(ii)}(\tau) = 2\Theta (\cos 2\pi \tau - \cos \pi d) - 2d \]  

(8)

and

\[ s_{0.5}^{(ii)}(\tau) = \text{sgn} (\cos 2\pi \tau), \]  

(9)

where sgn is the sign function.

(iii) Driving with triangular pulses, or “ramp modulation”, corresponds to

\[ s^{(iii)}(\tau) = \{ \tau \}, \]  

(10)

where the curly brackets denote the fractional part.

In all cases the modulation frequency is assumed to be small,

\[ \Omega \ll \omega. \]  

(11)

For this reason, the fast signal with frequency \( \omega \) can be called “driving”, while the slow signal with frequency \( \Omega \) can be denoted as the “energy-level modulation”.
B. Bloch equations and the rotating-wave approximation

With the Hamiltonian (1) the qubit dynamics can be described by the Bloch equations (as e.g. in Ref. [8]) for the components of the density matrix $\rho = \frac{1}{2} (1 + X\sigma_x + Y\sigma_y + Z\sigma_z)$:

\[
\begin{align*}
\frac{\dot{X}}{\hbar} &= -B_2 Y - \Gamma_2 X, \\
\frac{\dot{Y}}{\hbar} &= -B_2 Z + B_2 X - \Gamma_2 Y, \\
\frac{\dot{Z}}{\hbar} &= B_2 Y - \Gamma_1 (Z - Z_0) .
\end{align*}
\]

(12)

Here the phenomenological parameters $\Gamma_1 = T^{-1}_1$ and $\Gamma_2 = T^{-1}_2$ are the relaxation rates with decoherence rate $\Gamma_2 = \frac{1}{2} \Gamma_1 + \Gamma_\phi$, defined by the pure dephasing rate $\Gamma_\phi$. Decoherence defines the relaxation of $X$ and $Y$ towards $0$, while the relaxation of the diagonal component $Z$ is defined by the Maxwell-Boltzmann distribution for the given effective temperature $T_{\text{eff}}$, and it evolves towards $Z_0 = \tanh \left(\frac{\hbar \omega_0}{2k_B T_{\text{eff}}} \right)$.

It is often instructive to solve the Bloch equations analytically. There are several approaches, such as the adiabatic-impulse model and the rotating-wave approximation (RWA). We refer the interested reader to Refs. [7, 9] and references therein for the adiabatic-impulse and other models, while the RWA calculations are presented below in detail.

Based on the slowness of the energy-level modulation, Eq. (11), we can make use of the RWA, following Refs. [7, 9] and references therein for the adiabatic-impulse and other models, while the RWA calculations are presented below in detail.

To solve the Bloch equations, for the moment we assume that the system is driven close to resonance, where the “dressed energy distance” $\hbar \Delta \omega$ equals to the energy of $k$ photons, $\hbar \Delta \omega \approx k\hbar \Omega$. Then we omit the “fast-rotating” terms and leave only terms with $m = k$. With this, the r.h.s. of the Bloch equations does not contain any explicit time dependence. Then equating its l.h.s. to zero, we obtain the stationary solution. In particular, this gives the upper-level occupation probability, $P_+ = \frac{1}{2} (1 - Z)$. Summing all possible resonant terms, we obtain the qubit upper-level occupation probability

\[
P_+ \left( \frac{\Delta \omega}{\Omega}, \frac{\delta}{\Omega} \right) = \frac{1}{2} \sum_{k=-\infty}^{\infty} \frac{G_k^2 (\delta/\Omega) + \frac{1}{4} (\Delta \omega - k \Omega)^2 + \Gamma_1 \Gamma_2}{G_k^2 (\delta/\Omega) + \frac{1}{4} (\Delta \omega - k \Omega)^2 + \Gamma_1 \Gamma_2} .
\]

(20)

where $G_k(x) = G |\Delta_k(x)|$. We emphasize, that for a complex-valued $\Delta_k$, what matters is its absolute value.
C. Calculations for different modulations

As shown in Eq. (20), in order to obtain the upper-level occupation probability, one has to calculate the functions \( \Delta_k \). This is the subject of the present subsection.

(i) For the sinusoidal modulation, we can make use of the Jacobi-Anger expansion, which reads

\[
\exp(ix \sin 2\pi \tau) = \sum_{m=-\infty}^{\infty} J_m(x) e^{im2\pi \tau},
\]

(21)

where \( J_m(x) \) is the Bessel function of the first kind. Then, it is straightforward to see that

\[
\Delta^{(i)}_m(x) = J_m(x), \quad x = \frac{\delta}{\Omega}.
\]

(22)

It is useful to recall here the asymptote

\[
J_m(x) \approx \sqrt{\frac{2}{\pi x}} \cos \left[ x - \frac{\pi m}{2} - \frac{\pi}{4} \right].
\]

(23)

(ii) For the asymmetric latching modulation, by direct integration we obtain

\[
\Delta^{(ii)}_{d,m}(x) = 2 \frac{x \sin \left[ \pi d (m - 2 (1-d) x) \right]}{\pi (m + 2dx) (m - 2 (1-d) x)}.
\]

(24)

As mentioned before, since only \( |\Delta_m| \) matters in Eq. (20), we omitted factors with unit modulus. We will do this throughout.

In particular, for the symmetric rectangular driving with \( d = 0.5 \), Eq. (24) gives

\[
\Delta^{(ii)}_{0.5,m}(x) = 2 \frac{x}{\pi m^2 - x^2} \sin \left[ \frac{\pi}{2} (m - x) \right].
\]

(25)

(iii) For the ramp modulation, we have

\[
\Delta^{(iii)}_m(x) = \int_0^1 d\tau \exp \left[ i\pi (x\tau^2 - 2m\tau) \right].
\]

(26)

This can be rewritten in terms of the Fresnel integrals:

\[
\left| \Delta^{(iii)}_m(x) \right|^2 = \frac{1}{\pi x} \left[ C \left( \sqrt{\pi x} \left( 1 - \frac{m}{x} \right) \right) + C \left( \sqrt{\pi x} \frac{m}{x} \right) \right]^2 + \frac{1}{\pi x} \left[ S \left( \sqrt{\pi x} \left( 1 - \frac{m}{x} \right) \right) + S \left( \sqrt{\pi x} \frac{m}{x} \right) \right]^2,
\]

(27)

\[
S(y) = \int_0^y dt \sin t^2, \quad C(y) = \int_0^y dt \cos t^2.
\]

(28)

Such rewriting allows to use asymptotic approximations. In particular, when \( |y| \gg 1 \)

\[
S(y) \approx C(y) \approx \sqrt{\frac{\pi}{8}} \text{sgn} y,
\]

(29)

which gives

\[
\left| \Delta^{(iii)}_m(x) \right| \approx 1/\sqrt{x}.
\]

(30)
FIG. 1: Radio frequency (RF) wave power dependence of Landau-Zener-Stückelberg-Majorana (LZSM) interference of the spin resonance signal. (a) Schematic measurement set up. Instead of modulating the g-factor by \( V_G \), here we add the rf signal to the microwave signal with the power combiner. This set up is effectively equivalent to the set up of Fig. 1(a) because the rf signal is fed to the gate via a stray capacitance between the substrate and the gate. (b-e) the RF power dependence of the LZSM interference with fixed RF frequency of (b) 2 MHz, (c) 5 MHz, (d) 10 MHz, and (e) 20 MHz, respectively. (f-i) shows the corresponding calculations. For calculations the following parameters were used for all the graphs: \( G/2\pi = 1 \) MHz, \( \Gamma_1/2\pi = 0.2 \) MHz, \( \Gamma_2/2\pi = 1 \) MHz.

D. Limiting cases

Equation (20), together with the expression of \( \Delta_k(x) \) [Eqs. (22-26)], allows for an analytical treatment. Let us consider several illustrative limiting cases.

First, let us consider the symmetric latching modulation, with \( \Delta_k(x) \) given by Eq. (25). For low modulating frequencies, \( \Omega \ll \delta \), we have \( x = \delta/\Omega \gg 1 \) and \( |k| \gg 1 \). As a result, from Eq. (25) we obtain that, for any given value of \( x \), the contribution comes from the two \( k \)-th terms with \( k \approx \pm x \), for which we obtain \( \Delta_k(x) \approx 1/2 \). Inserting this result in Eq. (20) we find that the position of the resonances are at \( \Delta \omega = k\Omega \), which, for \( k = \pm x \), gives two lines at

\[
\Delta \omega = \pm \delta. \tag{31}
\]

At large modulating frequencies, \( \Omega \gg \delta \), we have \( x \ll 1 \) and \( k = 0 \). This is because for non-zero \( k \) we have \( \Delta_k \sim x/k^2 \rightarrow 0 \). As a consequence, the position of the resonance is defined by \( \Delta \omega = k\Omega \), which, for the main peak,
FIG. 2: Amplitude dependence of the square-wave modulation. (a-c) Similar measurements as Fig. 3(c) in the main text with different amplitudes of the square-wave modulation, (a) 16 mV, (b) 24 mV, and (c) 40 mV, respectively. (d-f) shows the corresponding calculations, using $\delta/2\pi = 12, 18, 30$ MHz for (d)-(f), respectively.

with $k = 0$, gives a zero shift of the resonance line:

$$\Delta \omega = 0. \quad (32)$$

Even more informative is the asymmetric latching modulation, with $d \neq 1/2$. For low modulating frequencies, $x \ll 1$, there are two characteristic values of $k$, defined from the denominator of Eq. (24). For $k = 2(1 - d)x$, we have $\Delta k \simeq d$ and $\Delta \omega = k\Omega$, so that

$$\Delta \omega = 2(1 - d)\delta. \quad (33)$$

For $k = -2dx$, we have $\Delta k \simeq 1 - d$, and

$$\Delta \omega = -2d\delta. \quad (34)$$

We can see that the two terms, with different $k$, define the positive and negative shifts of different signs, Eqs. (33-34), which for $d = 1/2$ reduce to Eq. (31). From Eq. (20) we can also define the heights of the two respective peaks, at $\Delta \omega = k\Omega$ and for given values of $k$’s we obtain

$$P_L^+ = \frac{1}{2} \frac{d^2}{d^2 + \lambda}, \quad P_H^+ = \frac{1}{2} \frac{(1 - d)^2}{(1 - d)^2 + \lambda}, \quad \lambda = \frac{\Gamma_1 \Gamma_2}{G^2}. \quad (35)$$

In this way, the asymmetric latching is defined by the $d$-dependent peaks at small modulating frequency, while for the large modulating frequency we again have $\Delta \omega = k\Omega$ with $k = 0$, i.e. the zero frequency shift, as above in Eq. (32), which is remarkably independent of $d$.

From our formulas, we can also estimate the modulating frequency $\Omega$, at which transition from one regime (high-frequency one, with the interference fringes) to another regime (low-frequency one, with two resonance lines described by Eq. (31)) takes place. For this, we can estimate from Eq. (20) both the width of the $k$-th resonance and the...
distance between neighboring resonances. Let us define the transition frequency $\Omega_*$ as the one at which those two values become equal. Then we obtain

$$\Omega_* = 2 \sqrt{\frac{\Gamma_2}{\Gamma_1}} \left( G_k^2 + \Gamma_1 \Gamma_2 \right) \lesssim 2 \Gamma_2.$$  \hspace{1cm} (36)

When $G$ is small, this gives $\Omega_* \approx 2 \Gamma_2$. For our parameters, with $\Delta_k \approx 1/2$, this gives $\Omega_* / 2\pi \approx 3$ MHz, in agreement with what we can see in both the simulations and the experiment in Fig. 2.

III. DETAILS OF EXPERIMENTAL AND CALCULATION RESULTS FOR THE MODULATED SINGLE SPIN

A. Sinusoidal modulation

The radio frequency (RF) wave power dependence of the Landau-Zener-Stückelberg-Majorana (LZSM) interference of the spin-resonance signal is summarized in Fig. 1. The intervals between the satellite peaks are defined by the RF frequencies, and the heights of the main and satellite peaks follow Bessel functions as a function of the RF power. Note that a small and very slow drift of the ESR frequency ($\sim 20$ MHz per week) is observed for fixed $V_G$ that seems to depend on the filling condition of liquid helium of the cryostat, probably due to the small change of the position of the superconducting magnet. The effect of this slow drift is negligible during the 1 hour measurement, but induces variations of the ESR frequency $f_0$ at $V_G = -0.36$ V from 9.00 to 9.01 GHz.

B. Symmetric square-wave modulation

The amplitude dependence of the square-wave modulation is shown in Fig. 2, which demonstrates that there are two characteristic frequencies. First, by increasing the modulating frequency, at $\Omega \approx \Omega_1 = 2 \cdot 2\pi$ MHz the transient behavior with interference fringes start to appear. Our calculations, demonstrate that this characteristic frequency is defined by the decoherence, $\Omega_1 = 2 \Gamma_2$ and it is independent of the modulating amplitude $\delta$. By further increasing
FIG. 4: Ramp modulations. (a) Measured ramp-modulation frequency dependence similar to Fig. 5(c) in the main text, but with inverted ramp waveform. (b) Intensity plot of the derivative $dP/+df$. Data is the same as in Fig. 5(d) in the main text.

In the frequency, we can observe a kind of motional averaging, with one principal peak at $\Delta f = 0$ [10] replacing the two peaks at $f_{1,2} - f_0 = \pm \delta$. The appearance of this peak depends on the amplitude $\delta$ and is independent on the decoherence rate; this happens at $\Omega \approx \Omega_2 = \delta/2$ [10].

C. Asymmetric latching modulation

The duty ratio dependence of the asymmetric square-wave modulations is shown in Fig. 3. Data for Fig. 4(h) and (i) in the main text are extracted from these, as well as from Fig. 3(c) in the main text for the 50% duty ratio.

D. Ramp modulation

We have checked the effect of time reversal symmetry of the ramp waveform [Fig. 4(a)]. It is nearly identical to Fig. 5(c) in the main text. Figure 4(b) is the derivative, $dP/+df$, of the Fig. 5(d) in the main text. Interference fringes with smaller wave length around the modulation frequency of 2 MHz are not clearly seen in the $dP/+df$ intensity plot [Fig. 5(d)].

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