

# Supplementary Information

## Coherent control of electron spin qubits in silicon using a global field

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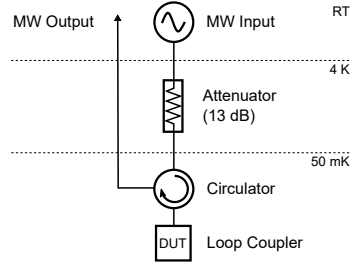
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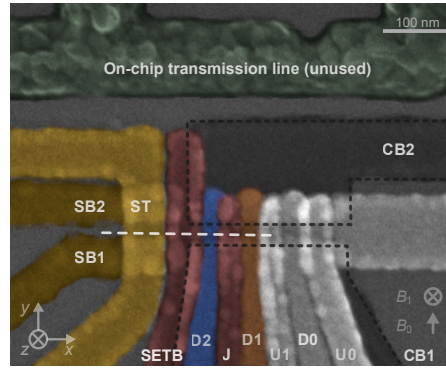
## SUPPLEMENTARY NOTE 1. EXPERIMENTAL SETUP AND QUBIT DEVICE

The setup used in this work is similar to the one in Ref.<sup>1</sup>, with additional attenuation on the microwave line to protect the device from room temperature noise (see Supplementary Fig. 1). All attenuators are thermally anchored to the 4 K stage.

The device in this work has a gate layout that replicates the one used in Ref.<sup>1</sup> (see SEM in Supplementary Fig. 2). However, it also includes an unused (floating) microwave transmission line (TL)<sup>2</sup> in the vicinity of the quantum dots, which is fabricated for conventional TL-based ESR measurements.



**Supplementary Figure 1: Microwave control setup diagram.** Schematic of the microwave components used in the experiment.



**Supplementary Figure 2: Device SEM image.** A false colored scanning electron microscope (SEM) image of a device identical to the one measured in this work. Gates U1 and U0 are unused in our experiments.

The abbreviations for the metallic gates of the device are:

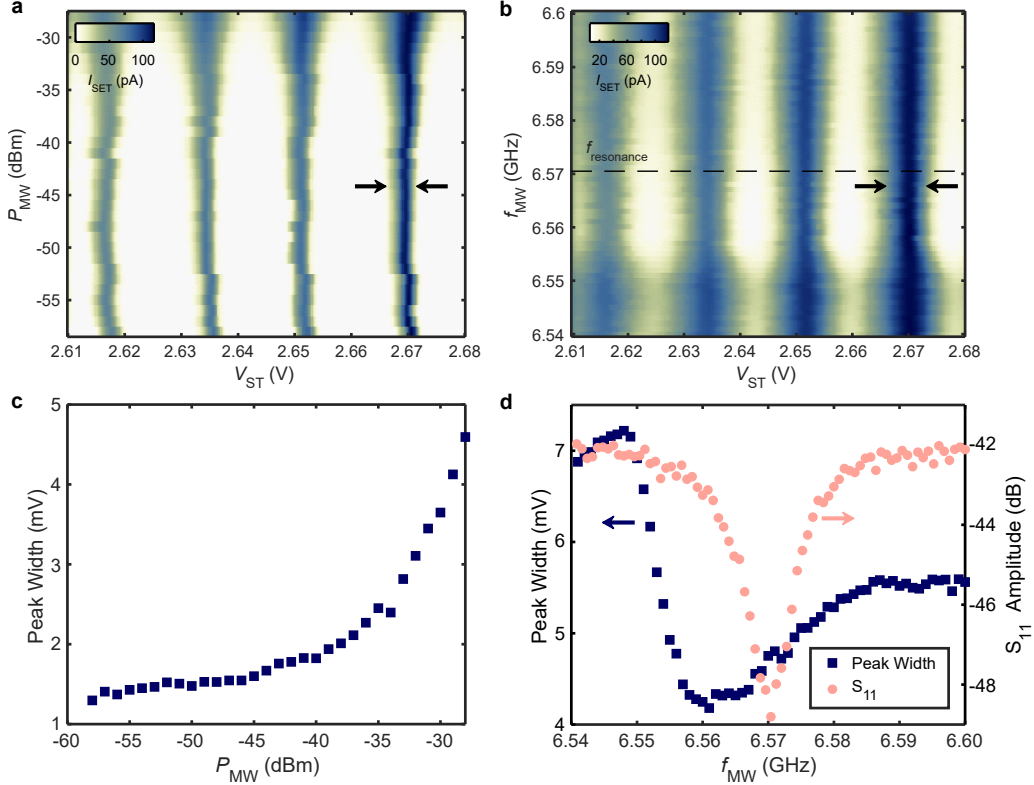
- **ST**: Sensor top gate
- **SBi**: Sensor barrier gate i
- **CBi**: Confinement barrier gate i
- **SETB**: SET barrier gate
- **Di**: Dot (Plunger) gate i
- **J**: Tunnel barrier (exchange) gate
- **Ui**: Unused gate (grounded)

## SUPPLEMENTARY NOTE 2. ELECTRIC FIELD GENERATED BY THE DIELECTRIC RESONATOR

We indirectly probe the electric field produced by the microwave signal sent to the loop coupler through an experiment where we monitor several Coulomb peaks of the SET with the microwave signal on.

We first perform a sweep of the microwave power with the frequency selected to be on-resonance with the DR (Supplementary Figs. 3(a) and (c)). Even though a slight broadening is observed for powers as low as -45 dBm, the peaks are still resolved at -28 dBm where we have observed coherent control (see Fig. 2 of the main text).

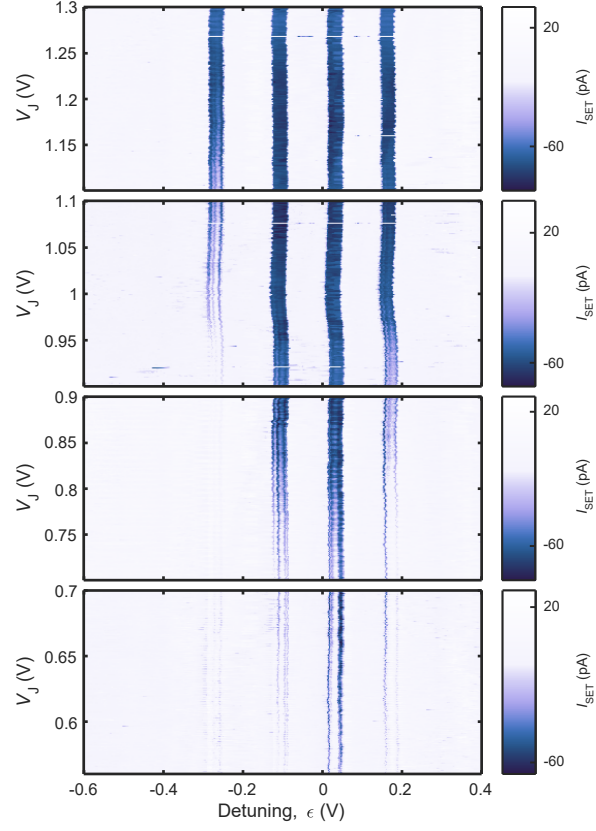
In order to investigate if the DR enhances the electric field, we also sweep the MW frequency (Supplementary Figs. 3(b) and (d)) at a fixed power over a range that covers the DR resonance. There is no evidence of an enhanced electric field within the DR resonance, where the Coulomb peak width appears to reduce slightly.



**Supplementary Figure 3: SET Coulomb peaks vs MW power and frequency.** SET Coulomb peaks measured as a function of an always-on microwave signal applied to the loop coupler, **a** Coulomb peaks vs. microwave power with  $f_{MW} = f_{resonance} = 6.5705$  GHz. **b** Coulomb peaks vs. microwave frequency with  $P_{MW} = -30$  dBm. **c-d** Fitted peak width of the peaks marked with black arrows in panels a and b, respectively. The DR  $S_{11}$  has been superimposed on panel (d).

### SUPPLEMENTARY NOTE 3. EXTENDED CHARGE STABILITY MAP

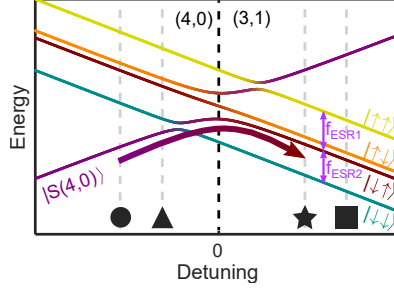
To further support our conclusion on the number of electrons in our double dot system, we provide a charge stability map taken over a larger range of J gate voltages in Supplementary Fig. 4 than the one in the main text (Fig. 1(d)). The number of transitions remains the same for a  $V_J$  range of 0.3V. The transitions become less visible at lower  $V_J$ , as the tunnel rates reduce below twice the AC excitation frequency (487 Hz), indicating that the J gate is successful in tuning the tunnel coupling between the dots.



**Supplementary Figure 4: Charge Stability Map.** An expanded version of the stability map in Fig. 1(d) with a larger J gate voltage range.

#### SUPPLEMENTARY NOTE 4. $|\downarrow\uparrow\rangle$ STATE INITIALIZATION

The energy diagram in Supplementary Fig. 5 visualizes how we initialize the two-spin system as singlet for all of the ESR measurements in this work. We first wait for 200  $\mu\text{s}$  in the voltage configuration indicated by the ‘circle’, which is somewhere in the (4,0) charge region, to prepare a singlet state with two electrons in the same dot. The remaining two electrons are in a lower orbital state, forming a closed shell and do not interact with the other pair. We then ramp to the point indicated by the ‘star’ in region (3,1) in order to perform a rapid adiabatic passage, where the  $T_-$  anticrossing is transversed fast in comparison to the  $S-T_-$  gap, but the  $|\downarrow\uparrow\rangle$  state is approached slowly in comparison to the difference in Zeeman frequencies.

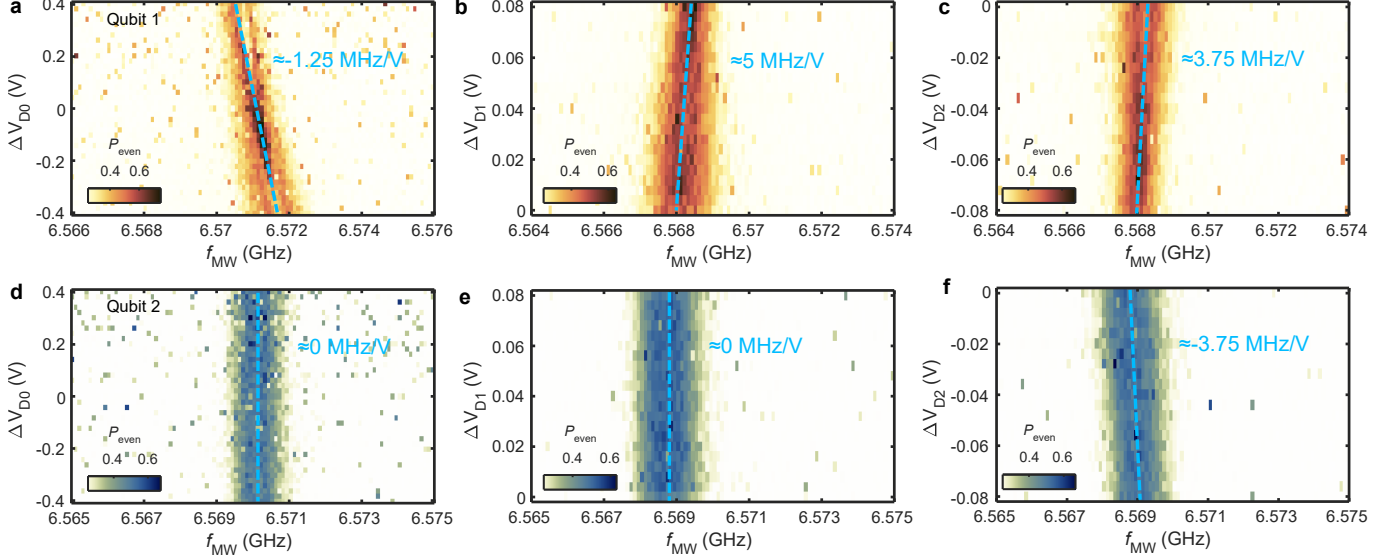


**Supplementary Figure 5: Energy diagram.** A schematic energy diagram depicting the energy levels of the eigenstates in the measured double dot system with respect to voltage detuning. The vertical black dashed line is where the charge transition occurs. The detuning points marked with black geometric shapes are the same as the voltage configurations in Fig. 1(d) and e of the main text. The curved arrow with color gradient shows how the singlet state is initialized.

## SUPPLEMENTARY NOTE 5. STARK SHIFT MEASUREMENTS

In order to identify the location of each qubit with respect to the gates, we measure the Stark shift effect that results from changing the potentials on the plunger gates D0, D1 and D2 (see Supplementary Fig. 6). The ESR frequency of Qubit 1 is mostly sensitive to D1, even though it is also affected by D0 and D2. As for Qubit 2, only the D2 gate has an observable effect on its frequency. These results indicate that Qubit 1 and 2 most likely reside under D1 and D2, respectively.

The Stark shift observed in our devices is caused by the spin-orbit effect due to the Si/SiO<sub>2</sub> interface, which presents roughness at the scale of the quantum dots<sup>3</sup>. This means that the electric field created by the gates will impact the spin both by pressing it further against the interface but also by moving the dot laterally. For our device design, in particular, this lateral movement has a dominant effect. As a result, the relationship between each individual gate voltage and the Stark shift that it causes varies from dot to dot, depending on the particular configuration of the roughness pattern.

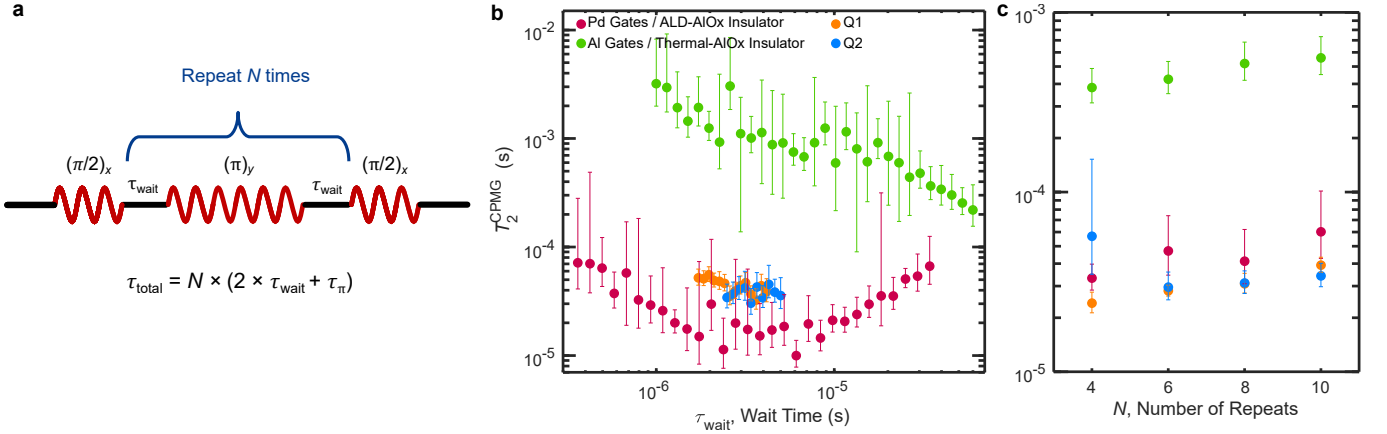


**Supplementary Figure 6: Stark shift measurements.**  $P_{\text{even}}$  measured as a function of  $f_{\text{MW}}$  and the DC voltages applied to plunger gates D0-D2 for Qubit 1 **a-c** and Qubit 2 **d-f**. The light blue dashed lines serve as guides showing how the ESR frequencies change with respect to the gate voltages. The numbers next to the lines correspond to approximate Stark shift values. The DC magnetic field  $B_0$  is applied in the [110] crystallographic direction and has a magnitude of 241 mT, whereas the MW field generated by the DR is along [001].

## SUPPLEMENTARY NOTE 6. CPMG MEASUREMENTS

The CPMG noise spectroscopy data shown in Fig. 3(c) is acquired using the ESR control sequence shown in Supplementary Fig. 7(a). The sequence starts with a  $(\pi/2)_x$  pulse to prepare the qubit in the xy-plane, then an even number  $N$  of  $(\pi)_y$  pulses are applied for refocussing. The sequence ends with another  $(\pi/2)_x$  pulse to rotate the qubit state back to the measurement (z) axis. The total sequence time,  $\tau_{\text{total}}$ , is the time over which the qubits are subject to decoherence and sets the bandwidth of the noise measurement, while the wait time,  $\tau_{\text{wait}}$ , determines the center frequency of the sequence filter function and therefore of the sampled noise.

Supplementary Fig. 7(b) shows the  $T_2^{\text{CPMG}}$  coherence times that are used to calculate the noise spectroscopy results presented in Fig. 3(c). The coherence of the Pd gates device (pink traces) are comparable to those of the qubits presented in this work (blue and orange traces), supporting the hypothesis that the major source of decoherence in our qubits is the gate material. Supplementary Fig. 7(c) reveals how the coherence times of the compared qubits vary as the number of  $(\pi)_y$  pulses is increased.



**Supplementary Figure 7: CPMG measurements.** **a** The sequence followed by all CPMG measurements reported in the main text. **b-c** The  $T_2^{\text{CPMG}}$  coherence times of the qubits corresponding to the CPMG noise spectra shown in Fig. 3(c), as a function of  $\tau_{\text{wait}}$  (b) and the number of  $(\pi)_y$  pulses applied (c). The errorbars indicate the 95% confidence interval bounds for the  $T_2^{\text{CPMG}}$  fits.

## SUPPLEMENTARY NOTE 7. OFF-RESONANCE SPIN CONTROL

As shown in Figs. 2(e) and (f), both qubits exhibit a weak residual coherent drive at frequencies outside the DR resonance. This indicates that there most likely exists some unintentional qubit driving mechanism(s) in addition to the direct magnetic fields generated by the dielectric resonator.

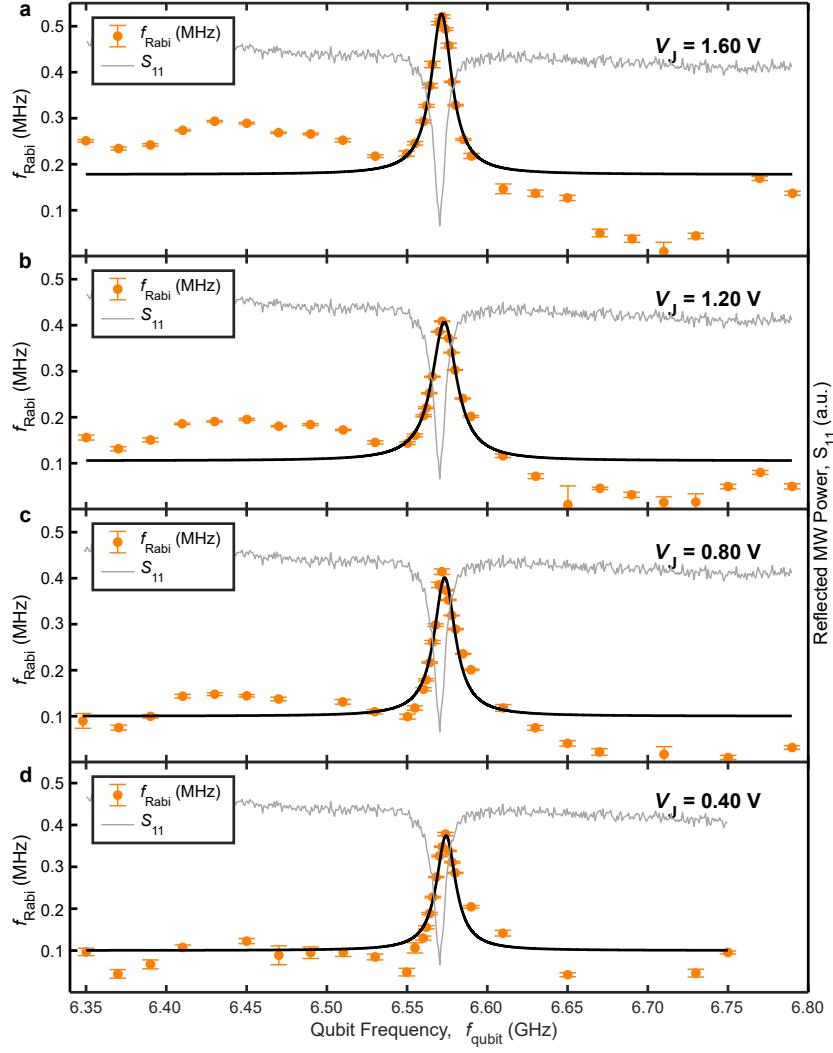
To investigate this further, we have repeated the  $f_{Rabi}$  vs.  $f_{Qubit}$  measurements shown in Figs. 2(e) and (f) for different J-gate voltages ( $V_J$ ). The result for Qubit 1 is depicted in Supplementary Fig. 8. The Rabi frequencies measured display a clear dependence on  $V_J$ . As  $V_J$  is lowered, the Rabi frequency reduces across the entire qubit frequency range. Supplementary Table 1 summarizes the changes in the maximum Rabi frequencies on-resonance with the DR and off-resonance, where an approximate constant peak height (defined as the difference in the on and off resonance Rabi frequencies) on top of a background level that changes with  $V_J$  is apparent. It is also observed that the enhancement in the Rabi frequency on-resonance with the DR (last column in Supplementary Table 1) is largest at the smallest value of  $V_J$ .

This supports our hypothesis on the existence of multiple driving mechanisms. One component of the qubit drive originates from the dielectric resonator, which is the desired drive in this work. There exists a second drive component whose strength is dependent on  $V_J$  and can be almost removed at sufficiently low voltages. The nature of this second qubit drive source warrants further investigation.

Recent work<sup>4</sup> on electric drive mechanisms in SiMOS qubits may shed some light on this anomalous drive. It was found that increasing the barrier gate voltage between the dots can turn a pure spin-only state to a spin-orbit mix, facilitating electrical control via an enhanced spin-orbit interaction. The resulting effect is fast electrical control at sufficiently high barrier-gate voltages, which could explain what we observe in Supplementary Fig. 8. Due to an enhancement of the spin-orbit interaction in our DQD, any stray electric fields – e.g. that may be generated by the resonator itself, the unused transmission line, or the metallic gates – are able to drive the qubits across a broad range of frequencies. This electric drive loses its effect at low J-gate voltages, where the spin-orbit interaction is weaker.

**Supplementary Table 1:** J-gate voltage dependency of Qubit 1 control.

| $V_J$ (V) | Max. $f_{Rabi}$ on-resonance (kHz) | Max. $f_{Rabi}$ off-resonance (kHz) | Difference (kHz) | Ratio |
|-----------|------------------------------------|-------------------------------------|------------------|-------|
| 1.6       | 522                                | 293                                 | 229              | 1.78  |
| 1.2       | 408                                | 195                                 | 213              | 2.09  |
| 0.8       | 414                                | 147                                 | 267              | 2.82  |
| 0.4       | 378                                | 122                                 | 256              | 3.10  |



**Supplementary Figure 8: Qubit 1 Control vs. J-gate voltage.** a-d Qubit 1  $f_{\text{Rabi}}$  dependency on  $f_{\text{Qubit}}$  for different J-Gate voltages ranging from 1.6 V to 0.4 V. The errorbars indicate the 95% confidence interval bounds for the  $f_{\text{Rabi}}$  fits.

## SUPPLEMENTARY NOTE 8. EXCHANGE COUPLING ESTIMATION

In order to rule out decoherence caused by the exchange coupling between the neighbouring qubits, we scan the qubit frequency as a function of the DC voltage on the barrier gate between the dots (J gate), looking for deviations from a traditional linear Stark shift<sup>5</sup>, which could indicate the onset of exchange coupling. In the presence of an exchange energy larger than the ESR linewidth ( $= 1/T_2^*$ ), an exponential variation of the resonant frequency is expected, and we should be able to observe four distinct resonances corresponding to the conditional spin flips for a randomly initialised pair of spins. We do not observe any of these qualitative features, and we further confirm that exchange is not a dominant source of decoherence by repeating the measurement at lower values of voltage bias on the barrier gate and obtaining similar results (data not shown).

## SUPPLEMENTARY REFERENCES

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