
Simultaneous high-fidelity single-qubit gates in a spin qubit array

In the format provided by the
authors and unedited

Contents

1	Micromagnet for power-efficient control	2
2	Heating effects in RB Simulations	3

1 Micromagnet for power-efficient control

High-fidelity single-qubit gates in our current device are achieved at the cost of relatively high microwave (MW) amplitudes, which limit the number of qubits that can be driven simultaneously due to increased decoherence and heating. To address this issue for future devices, we discuss modified micromagnet geometries that increase the transverse magnetic field gradient, referred to as the slanting or driving field gradient, thereby reducing the microwave power required for a given Rabi frequency.

Our design utilizes a gap-based micromagnet structure [1], featuring a lithographically defined gap of 400 nm and varying qubit-to-magnet distances ranging from 100 to 165 nm, owing to our overlapping-gate architecture. According to our simulations [2], the slanting field gradient is about ~ 1.4 mT/nm for our device geometry (see Extended Data Figure 8). To isolate the effect of micromagnet geometry, we assume a flat surface in the simulations, corresponding to a uniform vertical distance between the qubit and the micromagnet. Simulations show that halving the gap to 200 nm substantially enhances the slanting field, particularly for qubit–magnet distances below 150 nm. Additional improvement is possible by increasing the micromagnet thickness from 250 to 500 nm. With these design changes, and by reducing the metal and oxide thicknesses in the gate stack to bring the qubits closer to the magnet, we project a twofold increase in the slanting field gradient. Such an enhancement would enable equivalent gate speeds at half the MW power, thereby mitigating drive-induced decoherence and supporting high-fidelity operation across a larger number of qubits.

A potential concern when increasing the slanting field gradient—defined as the transverse magnetic field gradient $\partial B_z/\partial y$ responsible for electric dipole spin resonance operations—is the associated rise in dephasing gradients, particularly $\partial B_y/\partial x$, which convert charge fluctuations into detuning noise. This increase in dephasing gradients may degrade gate fidelity in the dephasing-limited regime (see Fig. 2 and Extended Data Figure 4 of the main text).

In the dephasing-limited regime, the single-qubit gate infidelity scales as $1 - F \propto \frac{\langle \beta^2 \rangle}{f_R^2}$, where $\langle \beta^2 \rangle$ is the variance of the quasi-static detuning noise, related to the noise power spectral density (PSD) (see Extended Data Fig. 4), and f_R is the Rabi frequency. Since $f_R \propto \partial B_z/\partial y$ and $\langle \beta^2 \rangle \propto (\partial B_y/\partial x)^2$ in the presence of charge noise, both the drive strength and effective detuning noise scale with the micromagnet gradient. As a result, their ratio—and therefore the gate error—remains approximately constant, assuming lin-

ear scaling of all gradients. However, our micromagnet simulations show that although $\partial B_y/\partial x$ increases with $\partial B_z/\partial y$, the scaling can be sublinear, indicating that increased drive strength does not necessarily result in a proportional increase in dephasing.

The primary benefit of a stronger gradient is not improved fidelity per se, but the ability to reach a given gate speed at lower MW power, mitigating heating and crosstalk during simultaneous multi-qubit operation. However, since our fastest gates are not yet limited by dephasing noise (see Fig. 2), a stronger gradient can also yield higher fidelities by suppressing other decoherence mechanisms.

A promising route is integrating nanomagnets directly into the gate stack using nanowires. Compared to conventional surface micromagnets, this approach occupies less lateral area, avoids interference with signal routing, and is compatible with three-dimensional backend integration, such as the SLEDGE architecture [3]. As such, it provides a more scalable approach for incorporating strong local magnetic gradients into large-scale spin qubit processors. Recent work predicts that these nanomagnets can provide driving gradients up to ten times larger than the micromagnet we are using in our experiments [4].

2 Heating effects in RB Simulations

Randomized benchmarking (RB) measurements shown in Fig. 2c of the main text exhibit a slight asymmetry in the fidelity as a function of detuning frequency, skewed toward positive detunings. This observation suggests additional effects beyond static frequency detuning, such as microwave-induced heating of the qubit. We therefore extended our RB simulations (see Methods) to include heating-induced frequency shifts and studied their impact on the detuning dependence.

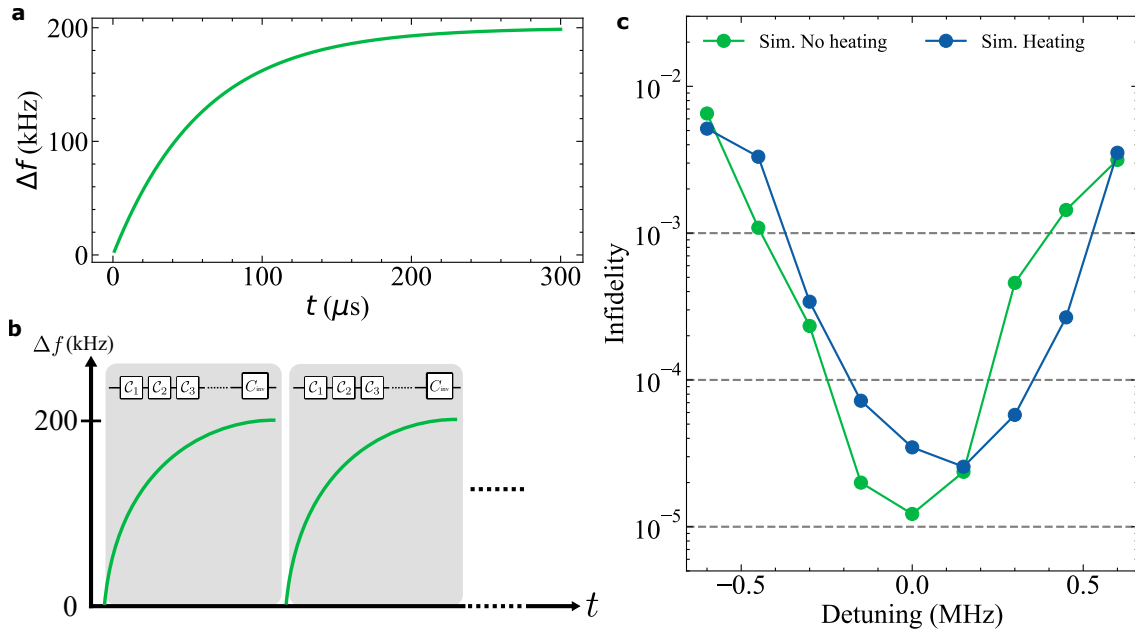
We model the heating effect of the microwave control signal by introducing a time-dependent frequency detuning in the RB simulations. The heating effect is modeled by the exponential model where the qubit frequency shift $\Delta f(t) = \Delta f_{\max}(1 - e^{-t/\tau})$ with $f_0 = 16473.4$ MHz, $\Delta f_{\max} = 200$ kHz and $\tau = 60$ μ s (Supplementary Fig. 1 (a)). This shift in frequency is included in the σ_z related term $\beta(t) = \beta_{\text{LF}} + \beta_{\text{IF}} + \beta_{\text{HF}}(t) + \Delta f(t)$ of the qubit Hamiltonian

$$\hat{H}_{\text{op}}(t) = 2\pi \left(\frac{\beta(t)}{2} \sigma_z + \frac{f_{\text{R}}}{2} (\cos(\phi) \sigma_x + \sin(\phi) \sigma_y) \right). \quad (1)$$

We choose the gate time $t_{\text{g}} = 250$ ns and estimate the frequency shift caused by the heating effect before each primitive gate. We track this frequency shift over the entire

RB Clifford sequence. This frequency shift is reset to zero after the Clifford sequence is applied, as shown in Supplementary Fig. 1 (b). This reset aligns with our experimental observations and is attributed to cooling during the readout and initialization stages preceding the next RB sequence.

We incorporate the heating-induced frequency shift into the RB simulations and simulate the RB fidelity at different detuning frequencies, as shown in Supplementary Fig. 1(c). The heating effect increases the minimum infidelity and shifts the optimal detuning point. Specifically, the infidelity minimum is shifted to a detuning of 200 kHz, consistent with experimental observations (see Fig. 2c of the main text).



Supplementary Figure 1: RB simulation with heating effect. **a** Modeled heating-induced qubit-frequency shift. **b** The qubit frequency is shifted according to the gate time $t_g = 250$ ns for each primitive gate. After each Clifford sequence, the frequency shift is reset to zero. This procedure is repeated for all simulated Clifford sequences. **c** Simulated detuning dependence without heating (green) and with heating (blue). Circles denote the simulated detuning points.

Supplementary References

- [1] Yoneda, J. *et al.* Robust micromagnet design for fast electrical manipulations of single spins in quantum dots. *Applied Physics Express* **8** (8), 084401 (2015) .
- [2] Ortner, M. & Coliado Bandeira, L. G. Magpylib: A free python package for magnetic field computation. *SoftwareX* **11** (100466), 100466 (2020) .

- [3] Weinstein, A. J. *et al.* Universal logic with encoded spin qubits in silicon. *Nature* **615** (7954), 817–822 (2023) .
- [4] Tadokoro, M. *et al.* Designs for a two-dimensional si quantum dot array with spin qubit addressability. *Sci. Rep.* **11** (1), 19406 (2021) .