Long-Range Coupling of Silicon Flip-Flop Qubits: Interplay Between Electric Dipole-Dipole and Metal Floating-Gate Interactions

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Abstract: This study explores long-range silicon flip-flop qubit coupling to mitigate routing constraints by investigating the interplay between electric dipole-dipole and metal floating-gate interactions. Optimization of two-qubit gates is achieved, and noise effects on gate fidelity are studied.

Scaling up of silicon-based quantum processors requires dense qubit arrays, even for flip-flop (FF) qubits [1, 2], where the large number of control and readout electrodes still creates metal-gate routing constraints [3]. Simply increasing the physical separation between FF qubits would alleviate routing congestion but would simultaneously weaken the native electric dipole-dipole coupling, degrading two-qubit gate performance.

To address this trade-off, we develop a theoretical framework for metal floating-gate (MFG) couplers to enable long-range interactions between FF qubits. Starting from established models [4,5], we extend a physics-based description of the MFG to consistently capture the electrostatically mediated coupling between two spatially separated FF qubits in a realistic device environment (Fig. 1).

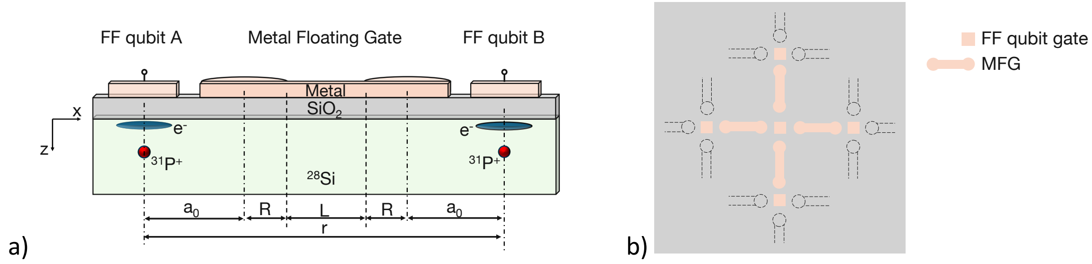

Fig. 1 a) Schematic cross section of a MOS device showing two FF qubits (qubit A and B), each with a corresponding $^{31}P^{+}$ phosphorus atom and its bonded electron e^{-}. The FF qubits are displaced by a distance r, ranging from 360 nm to 8 μm, coupled by a MFG of length L with circular endings of radius R=20 nm. The distance between each FF qubit and the centre of the corresponding closest circular end of the MFG is set to a_0=40 nm. The MFG width is set to 40 nm. b) Top view of a schematic of five FF qubits coupled by four MFGs, scheme potentially scalable to larger 2D arrays (dashed lines).

The model incorporates geometric parameters, capacitive effects, and spatial configuration, providing direct insight into the dependence of coupling strength on distance and device layout. This allows us to investigate the interplay between native electric dipole–dipole coupling and MFG-mediated interaction, with the aim of assessing whether and under which conditions the MFG may provide a dominant or corrective contribution to the overall coupling.

Building on this framework, we formulate the control problem for two-qubit gate operations under realistic dynamical constraints. Control sequences for $\sqrt{\mathrm{iSWAP}}$ gates are derived through a hybrid optimization approach combining a genetic algorithm with a Newton–Raphson refinement step, explicitly accounting for signal transients. This methodology enables the exploration of the control landscape while maintaining physical consistency with the underlying model.

Numerical analyses are being carried out to explore the behaviour of the system and to qualitatively assess the impact of qubit spacing on gate performance. The effect of low-frequency charge noise, modeled with a 1/f spectrum, is also being incorporated, although a systematic evaluation is still in progress.

Our framework explores how metal floating-gate couplers might mitigate routing constraints in silicon FF qubit-based 2D arrays (Fig. 2), intended for use with topological quantum error correction codes, such as surface codes. By analyzing the interplay between electric dipole-dipole and mediated interactions, this study assesses pathways for engineering long-range quantum gates.

References

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