# Bosonic state preparation through coupling with semicon-spin qubit using numerically optimized pulse sequences

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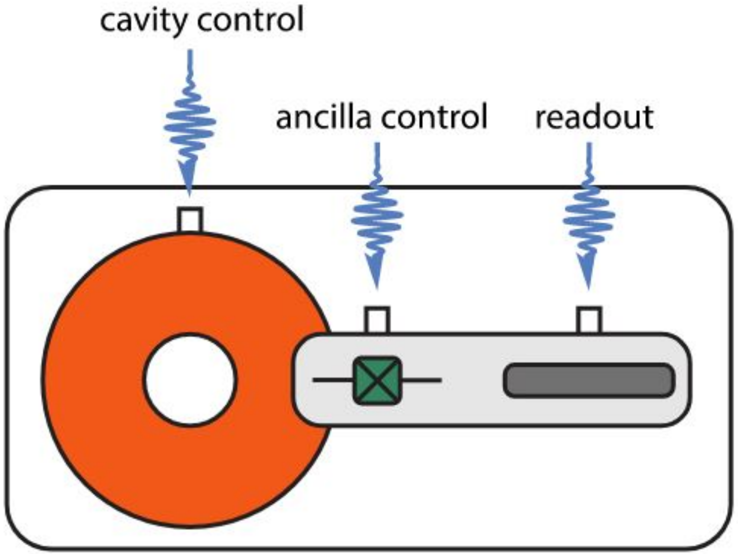
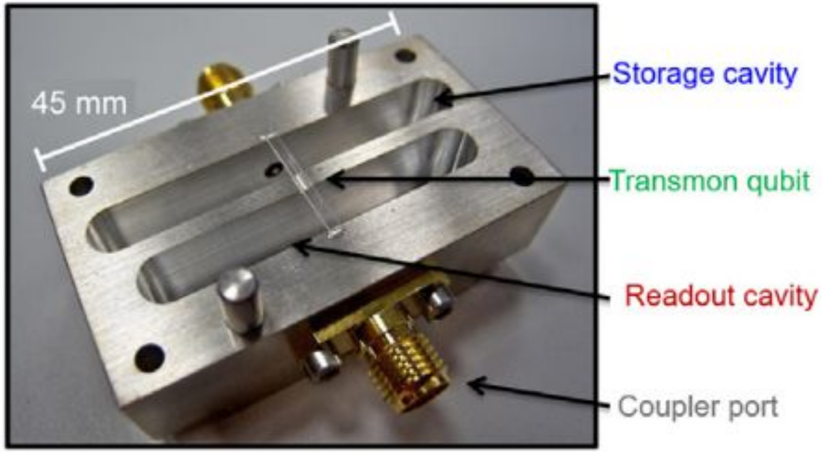
# Motivation for **bosonic-modes-encoded qubits**

| Challenges, QEC approaches | Long coherence time | Fast quantum computation | Good scalability |
| --- | --- | --- | --- |
| Traditional approach: encode 1 logical qubit into multiple physical qubits | Multiple physical qubits introduce more decoherence | Difficult to control multiple physical qubits at the same time | Less scalable |
| Alternative: **encode 1 logical qubit into multiple bosonic modes** (e.g. photonic modes in a superconducting cavity) | Bosonic modes stored in cavity have less loss channels, hence longer coherence | Only require control of one physical device | Potentially more scalable |

# Cavity dispersively coupled to a ancilla qubit for additional control over cavity state




Left figure: Quantum information processing with bosonic qubits in circuit QED, Atharv Joshi et al. 2021
Right figure: Quantum control of bosonic modes with superconducting circuits, Ma, 2021

# Motivation for semiconductor-spin control qubit over superconducting control qubit

1. Possibly larger (coherence time) / (single gate time limit) ratio
    a. Semicon-control qubits generally have more control channels than superconducting ones

Table 1 | **Current state of the art for semiconductor qubits**

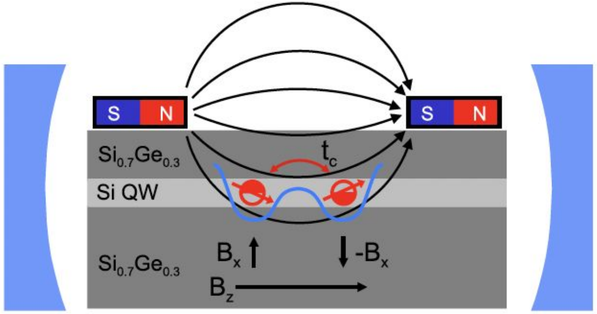
| Qubit type | Characteristic timescales (s) | | Quantum computation | | Quantum sensing | |
|---|---|---|---|---|---|---|
| | $T_1$ | $T_{2DD}$ | Single-qubit gate time | Single-qubit fidelity | Quantity | Sensitivity |
| Gated charge | 30 ns (REF. [273]) | 7 ns (REF. [11]) | ~0.1 ns (REF. [12]) | 86%[273] | Charge | ~$10^{-4}$ e/$\sqrt{(\mathrm{Hz})}$ at 1 Hz (REF. [11]) |
| Gated spin | 57 s (REF. [54]) | 28 ms (REF. [24]) | 25 ns (REF. [25]) | 99.96%*[274] | Magnetic field gradients | 50 pT/$\sqrt{\mathrm{Hz}}$ (REFS [24,167]) |
| Shallow dopants (electron) | >1 h (REF. [101]) (ens), 10 s (REF. [120]) | 10 s (REF. [104]) (ens), 0.56 s (REF. [124]) | ~100 ns (REF. [82]) | 99.94%*[127] | Magnetic field (AC) | 18 pT/$\sqrt{\mathrm{Hz}}$ (REF. [124]) |
| Shallow dopants (nucleus) | >days[66] | 3 h (REF. [111]) (ens), 35.6 s[124] | ~20 µs (REF. [66]) | 99.98%*[126] | Magnetic field (AC) | 2 nT/$\sqrt{\mathrm{Hz}}$ (REF. [131]) |
| Colour centres | >1 h ($NV^-$ diamond)[175] | 1 s ($NV^-$ diamond)[175] | <20 ns (REF. [173]) | 99.995%* ($NV^-$ diamond)[275] | Magnetic field (DC) | 50 pT/$\sqrt{\mathrm{Hz}}$ (REF. [244]) (ens), 500 nT/$\sqrt{\mathrm{Hz}}$ (REF. [243]) |
| | | | | | Magnetic field (AC) | 32 pT/$\sqrt{\mathrm{Hz}}$ (REF. [276]) (ens), 4.3 nT/$\sqrt{\mathrm{Hz}}$ (REF. [245]) |
| | 10 s (SiV SiC)[277] | >20 ms (SiV SiC)[277] | | 99.984%* (divacancy SiC)[221] | Temperature | 100 mK/$\sqrt{\mathrm{Hz}}$ (REFS [250,251]) (SiV in diamond, SiC) |
| | | | | | Electric field | $10^{-5}$ V · µm$^{-1}$ / $\sqrt{(\mathrm{Hz})}$ (REF. [278]) |

Table from: Semiconductor qubits in practice, Anasua Chatterjee

# Cavity with Double Quantum Dots (DQD) ancilla

- Single spin DQD Hamiltonian

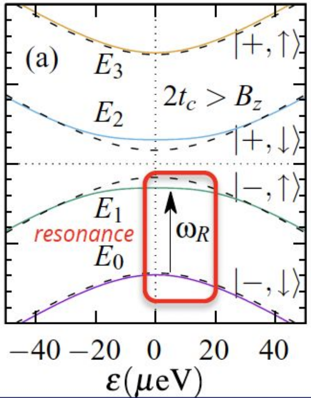
$$H_{\mathrm{DQD}} = \underbrace{\tfrac{1}{2}\epsilon\tau_z + t_c\tau_x}_{\text{orbital}} + \underbrace{B_z\sigma_z}_{\text{Zeeman}} + \underbrace{B_x\sigma_x\tau_z}_{\text{spin-orbit}}$$

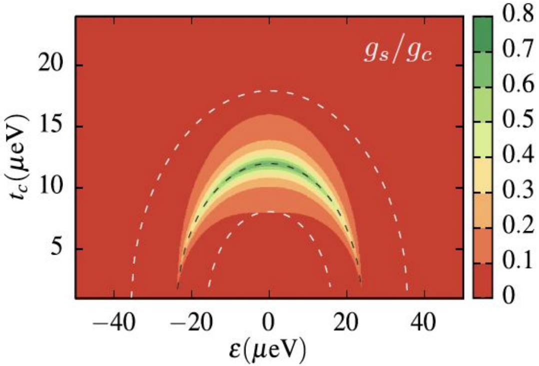



Figures from Benito et al., PRB **96**, 235434 (2017

- Electric dipole interaction $H_{\mathrm{int}} = g_c(a + a^\dagger)\tau_z$
  - couples spin-charge hybridized states in DQD eigenbasis

- At resonance: effective two-level Jaynes-Cummings Hamiltonian
  - tunable spin-photon coupling $g_s$
  - Independent tuning knobs for spin-photon coupling and Rabi driving



# Displacement operator gate (D) and SNAP gate (S)

1. Displacement gate:
   a. Direct unitary transformation on the oscillator
   b. Generated by a linear drive on the cavity
2. Selective Number-dependent Arbitrary Phase gate
   a. Indirect control on the oscillator through ancilla
   b. To realize SNAP gates, weakly drive the ancilla with multiple frequency components

$$D(\alpha) = \exp(\alpha a^\dagger - \alpha^* a),$$

$$H_\mathrm{C} = \epsilon_\mathrm{C}(t)\mathrm{e}^{\mathrm{i}\omega_\mathrm{C} t} a^\dagger + \mathrm{H.c.}$$
with $\alpha = -\mathrm{i}\int \epsilon_\mathrm{C}(t)\mathrm{d}t.$

$$S(\vec{\varphi}) = \sum_{n=0}^{\infty} \mathrm{e}^{\mathrm{i}\varphi_n} |n\rangle\langle n|,$$

$$H_\mathrm{T} = \epsilon_\mathrm{T}(t)\mathrm{e}^{\mathrm{i}\omega_\mathrm{T} t}|g\rangle\langle e| + \mathrm{H.c.}$$
with $\epsilon_\mathrm{T}(t) = \sum_n \Omega e^{\mathrm{i}(\phi_n(t) - n\chi t)}$

Quantum control of bosonic modes with superconducting circuits, Ma et al. 2021

# State preparation using D, S gates: analytic VS numerical

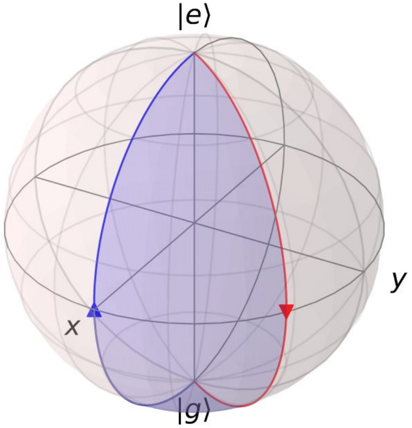
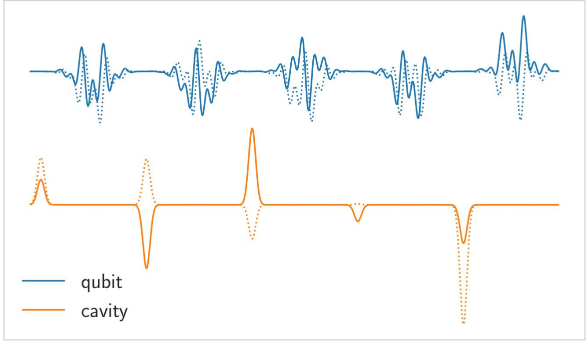
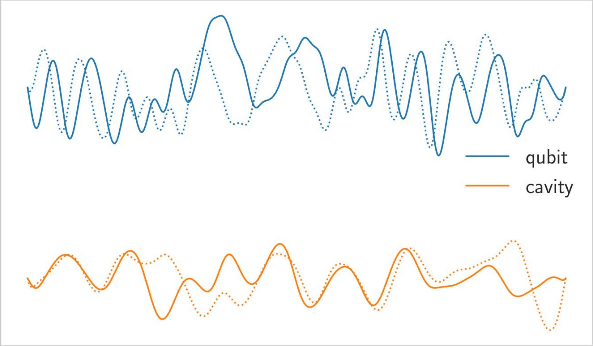



Figure 2.7: **Geometric phase on the Bloch sphere**. By performing a set of rotations which bring the energy eigenstates back to themselves, we effectively perform a rotation around the z axis, with angle given by the enclosed area. Unlike the cavity case, the phase is state-specific. This imparts one phase to the state $|g\rangle$, and the opposite phase to the state $|e\rangle$.

analytical




numerically optimized




Figures taken from: Controlling Error-Correctable Bosonic Qubits, Philip Reinhold PhD thesis, 2019
Quantum control of bosonic modes with superconducting circuits, Ma et al. 2021
Universal control of an oscillator with dispersive coupling to a qubit, Stefan Krastanov et al. 2015

# My tentative main task: bosonic state preparation through numerically-optimized pulse sequences

1. GRadient Ascent Pulse Engineering (GRAPE)
   a. numerical optimization algorithm
2. QuTiP
   a. Open-source software for simulating the dynamics of open quantum systems

# Possible further tasks

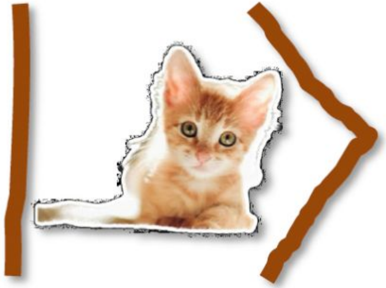
1. Arbitrary bosonic state preparation
    a. through analytic D, S-pair pulse sequences
    b. Through numerically optimized pulse sequences
2. Unitary gate design
    a. Choose a 2-qubit gate (e.g. C-NOT gate)
        i. -> gate matrix in logical qubit basis
        ii. -> find gate matrix in physical qubit basis (dependent on QEC code)
        iii. -> find the physical implementation of such a gate on my physical system (sequences of control pulses)

# Thank you!

References:

1. Introductory Quantum Optics, Christopher C. Gerry and Peter L. Knight
2. Controlling Error-Correctable Bosonic Qubits, Philip Reinhold PhD thesis, 2019
3. Optimal dispersive readout of a spin qubit with a microwave resonator, B. D'Anjou and Guido Burkard, 2019
4. Quantum control of bosonic modes with superconducting circuits, Ma et al. 2021
5. Universal control of an oscillator with dispersive coupling to a qubit, Stefan Krastanov et al. 2015
6. Quantum information processing with bosonic qubits in circuit QED, Atharv Joshi et al. 2021

# Kitten code (simplest binomial code)



- Quantum error correction
  - Uses redundancy of a large Hilbert space of ***many physical two-level systems***

- Bosonic QEC
  - Uses same redundancy, but in infinitely large Hilbert space of ***a single physical system***
    i.e. one quantum harmonic oscillator, e.g. 3D cavity or 2D planar superconducting resonator

- Kitten code:

$$\begin{cases} |0_L\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle + |4\rangle\right) \\ |1_L\rangle = |2\rangle \end{cases}$$

  - Designed to correct single photon loss errors
  - Error maps even to odd parity states, enables recovery

$$|\psi_L\rangle = \alpha|0_L\rangle + \beta|1_L\rangle$$

photon loss: $\hat{a}|\psi_L\rangle = \sqrt{2}\left(\alpha|3\rangle + \beta|1\rangle\right) \xrightarrow[\textit{recovery}]{} \sqrt{2}\left(\alpha|0_L\rangle + \beta|1_L\rangle\right) \propto |\psi_L\rangle$

  - Same mean photon number protects against dephasing – environment does not gain information about state

# Example DQD device

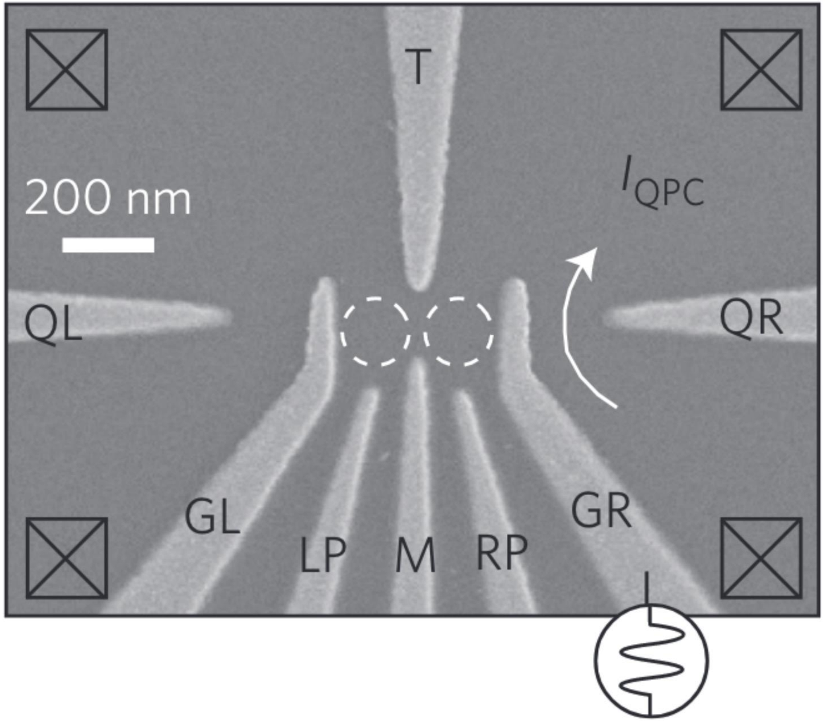



Figure: Scanning electron microscopy image of a kind of DQD device

Microwave-driven coherent operation of a semiconductor quantum dot charge qubit, Dohun Kim et al. 2015