Cryogenic Circuits and Systems for Qubits Readout

Mathilde OUVRIER-BUFFET
Outline

- Introduction
- Spin qubit readout
- A scalable approach
- Conclusion
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• A scalable approach
• Conclusion
# Qubit technologies

<table>
<thead>
<tr>
<th></th>
<th>Superconductor</th>
<th>Si spin</th>
<th>Ion traps</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Size</strong></td>
<td>100μm$^2$</td>
<td>100nm$^2$</td>
<td>1mm$^2$</td>
</tr>
<tr>
<td><strong>Fidelity</strong></td>
<td>99.3%</td>
<td>98%</td>
<td>99.9%</td>
</tr>
<tr>
<td><strong>Speed</strong></td>
<td>100 ns</td>
<td>5 μs</td>
<td>100 μs</td>
</tr>
<tr>
<td><strong>Variability</strong></td>
<td>3%</td>
<td>0.1-0.5%</td>
<td>0.0001%</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>50mK</td>
<td>0.1-1K</td>
<td>300K</td>
</tr>
</tbody>
</table>

Scalability

- **Issue:**
  - Laboratory instrumentation for RT* electronic control/readout interface
  - Large interconnects number

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* Room temperature
Scalability

• Issue:
  – Laboratory instrumentation for RT electronic control/readout interface
  – Large interconnects number


• Solution:
  – CMOS IC electronic interface
  – Frequency multiplexing
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Spin Qubit

Double Quantum Dot (DQD)

- Trap electrons at cryogenic temperature
- Singlet/Triplet Qubit
- Focus area: (1,1)-(0,2) charge transition

Spin-to-charge conversion

Double Quantum Dot (DQD)
Spin-to-charge conversion

Double Quantum Dot (DQD)

1. Sensor initialization in down state
Spin-to-charge conversion

Double Quantum Dot (DQD)

1. Sensor initialization in down state
2. Qubit manipulation
Spin-to-charge conversion

Double Quantum Dot (DQD)

1. Sensor initialization in down state
2. Qubit manipulation

Singlet state $|\downarrow\uparrow\rangle$

Triplet state $|\downarrow\downarrow\rangle$

Pauli spin blockade

Spin-to-charge conversion

Double Quantum Dot (DQD)


Gate-based reflectometry

Sub-10GHz range

$C_q$: state-dependent capacitance
Gate-based reflectometry

- Amplitude/phase shift in the reflected signal
- State-dependent phase-shift

\[ \Delta \varphi = \arctan \left( -Q_{S11} \frac{C_q}{C_0 + C_c} \right) \]
Resonator impact

- State-dependent phase-shift: \( \Delta \varphi = \arctan \left( -Q_{S11} \frac{C_q}{C_0 + C_c} \right) \)

- Reflection quality factor: \( Q_{S11} = Q_0 \frac{2k}{(k^2 - 1)} \)

- Coupling coefficient: \( k = \frac{Q_0}{Q_e} \)

\[ \Delta \varphi (\text{rad}) \]

<table>
<thead>
<tr>
<th>Coupling coefficient ( k )</th>
<th>Model</th>
<th>High ( Q_0 ) - ( C_0=100\text{fF} )</th>
<th>Low ( Q_0 ) - ( C_0=100\text{fF} )</th>
<th>Low ( Q_0 ) - ( C_0=900\text{fF} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.6</td>
<td>Theory</td>
<td>Model</td>
<td>Theory</td>
</tr>
<tr>
<td>1.5</td>
<td>1.4</td>
<td>High ( Q_0 ) - ( C_0=100\text{fF} )</td>
<td>Model</td>
<td>High ( Q_0 ) - ( C_0=100\text{fF} )</td>
</tr>
<tr>
<td>2</td>
<td>1.2</td>
<td>Low ( Q_0 ) - ( C_0=100\text{fF} )</td>
<td>Low ( Q_0 ) - ( C_0=900\text{fF} )</td>
<td>Low ( Q_0 ) - ( C_0=900\text{fF} )</td>
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<td>2.5</td>
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<tr>
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<tr>
<td>4</td>
<td>0.4</td>
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<td></td>
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<tr>
<td>4.5</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td></td>
<td></td>
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</tbody>
</table>
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Cryogenic frequency multiplexing

Multi-tone signal
Sub-10GHz range
Multi-qubits readout system

- Sub-10GHz range
- $f_i$ from 2 GHz to 4.5 GHz
- 500 MHz spacing

- CMOS IC in 45nm SOI
Multi-qubits readout system

Strong attenuation (≈ -50 dB)
Multi-qubits readout system

Strong attenuation (~ -50 dB)

Cryogenic MUX

$C_0 = 900 \, \text{fF}$

$Q_0 = 60$
Multi-qubits readout system

Strong attenuation (~ -50 dB)

Cryogenic MUX
- $C_0 = 900 \text{ fF}$
- $Q_0 = 60$

Quantum capacitance
- $C_{q,T} = 0 \Leftrightarrow \downarrow\downarrow\downarrow$ T-state
- $C_{q,S} = 1 \text{ fF} \Leftrightarrow \downarrow\uparrow\uparrow$ S-state

Multi-qubits readout system

Performances (AsGa, CMOS)
NF = 0.1 dB (@4K)
G = 35 dB

Strong attenuation (~ -50 dB)

Cryogenic MUX
C₀ = 900 fF
Q₀ = 60

Quantum capacitance
Cₜₐₜ = 0 ↔ |↓↓⟩ T-state
Cₜₛ = 1 fF ↔ |↓↑⟩ S-state

Multi-qubits readout system

\[ \varphi_n = \arctan \left( \frac{Q_n}{I_n} \right) \]

\[ A = \sqrt{I_n^2 + Q_n^2} \]

\[ \text{BW}_{BB} = 1.3 \text{ MHz} \]

\[ \Rightarrow t_r = 1 \mu s \]
Readout fidelity

AC noise analysis

• RMS noise: $v_{n,RMS} = \sqrt{\int PSD \cdot df} = \sigma$

• Pure states distributions: $n_T(\theta) = \frac{1}{\sqrt{2\pi}\sigma_T} e^{\frac{(\theta - \theta_T)^2}{2\sigma_T^2}}$
  
  $n_S(\theta) = \frac{1}{\sqrt{2\pi}\sigma_S} e^{\frac{(\theta - \theta_S)^2}{2\sigma_S^2}}$

• State fidelities: $F_S = 1 - \int_{-\infty}^{\theta_{th}} p_S(\theta) d\theta$
  
  $F_T = 1 - \int_{\theta_{th}}^{+\infty} p_T(\theta) d\theta$

• Readout fidelity: $F_R = \frac{F_T + F_S}{2}$
Readout fidelity

Resonator coupling

![Diagram showing multi-tone oscillator connection and resonator coupling with variables and coupling coefficient graph showing readout fidelity as a function of coupling coefficient.](image-url)
Readout fidelity

Power

LNA noise figure (dB)

Readout fidelity (%)

LNA NF = 0.1 dB
LNA NF = 0.03 dB

Noise figure

Multi-tone oscillator

300K

4K

-120
-100

P_R (dBm)

50
60
70
80
90
100

-100
-90
80
90
100

Pr = -110 dBm
Pr = -100 dBm
Pr = -90 dBm

0.01
0.1
1

WMC-3

IEEE International Microwave Symposium
6 - 11 June 2021, Atlanta, GA
Readout fidelity

- Phase-shift depends on the relaxation time $T_1$

$$\theta_S = \theta_T + a_1 e^{-t_r/T_1}$$

$T_1 = 2.7 \, \mu s$
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Conclusion & perspectives

• System analysis of multi-qubits reflectometry:
  – the impacting parameters on the Figure of Merit
  – theoretical constraints of a scalable readout approach

• Multi-tone oscillator design
Thank you!
References


