Photon Emission from a Cavity-Coupled Double Quantum Dot

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Motivation

- From cavity quantum electrodynamics (QED) via circuit QED to quantum dot QED
- Use emitted photons as a quantum bus in a hybrid device
- Possible single photon source
Cavity QED

- Coupling between matter and light in a resonator

- Use a cavity because bigger interaction (field confinement, several photon passings)

In the limit of a two-level system and a single photon mode:

→ Cavity QED

- Manifold of effects, i.e. enhancement/inhibition of spontaneous emission

- Strong Coupling: Jaynes-Cummings Hybridization

Circuit QED

- Replace atom by artificial atom (not Rydberg), Non-linear LC circuit
- Josephson junction leads to Charge Qubit, Flux Qubit, Phase qubit
- Use a superconducting transmission line as cavity
- Much larger dipole of atom due to larger dimensions → stronger coupling
- Very successful in terms of quantum computation

You et. al Nature, 474(2011) & Wallraff et al. arxiv:0411174
Quantum Dot QED

• Use GaAs double quantum dot (DQD) coupled through a metallic gate to the resonator

• For a fixed electron number within the dots they do not see a change in cavity transmission because of large charging energy (~meV)

The hybrid device

- Si/SiO₂ wafer, deposit Nb on top
- Aggressive wet etch to form a half-wavelength resonator
- Patterning of bottom electrodes, insulate with SiNₓ
- Deposit InAs nanowires, contact them, source is connected to cavity
Quantum Dot QED II

- Use InAs nanowire, because of larger SO-Coupling

- Operate DQD at charge degeneracy, energy is tunable via detuning and tunnel coupling

\[
\omega_a = \frac{\Omega}{\hbar} \quad \Omega = \sqrt{\epsilon^2 + 4t_C^2}
\]

- If energy of DQD and cavity are similar the cavity is damped

\[
\Delta = \omega_a - \omega_0
\]

- In dispersive limit (\(\Delta > g_c\)), phase shift

\[
\phi = -\arctan\left(\frac{2g_C^2}{\kappa \Delta}\right)
\]

- \(g_C/2\pi \sim 30 \text{ MHz}\)

Photon Emission Study

- $f_0 \sim 7.862 \text{ GHz}$; $Q \sim 3600$
- $g_0/2\pi \sim 16\text{MHz}$

- How does transport through the dot change cavity dot interaction?

- During inelastic tunneling, $e^{-}$ have to lose energy:→ phonons, photons

- Can one collect the emitted photons in the cavity?

- Go to inelastic regime:→ apply bias
Biasing the quantum dot

- 2.5 mV $V_{SD}$ results in bias triangles (up to $I = 8\text{nA}$!)

- Transmission through the cavity is measured as a function of $V_R, V_L$

- Gain for $\varepsilon > 0$

- Expect maximal gain for $\Omega \sim 33\mu\text{eV}$
- $t_C \sim 16.4\mu\text{eV} \rightarrow \varepsilon_{\text{max}} \sim 1\mu\text{eV}$

- But: Gain observed up to $\varepsilon \sim 200\mu\text{eV}$
- Not only first order process?
Stimulated emission

- Stimulated emission if photon emission rate is larger than cavity loss
- Lower tunnel barriers to increase photon emission
- Hot spots with gain ~ 15
- Increase in Q
- Cavity drive still on, search for direct evidence of photon emission
Quantum Dot Lasing

- Turn on drive, connect cavity to a cryogenic HEMT
- Photon emission rate 10 MHz above amplifier background
- Photon number in the cavity

\[ \frac{2\Delta \Gamma_p}{\kappa} \approx 2 \]
- Efficiency measure:

\[ \beta \geq \frac{2\Delta \Gamma_p}{(I/e)} \approx 0.4 \times 10^{-3} \]
- Strong competition with other relaxation mechanisms
Summary

• DQD – cavity interaction leads to gain in cavity transmission (up to 15), correlated with inelastic tunneling

• Direct observation of photon emission

• But: very poor efficiency, due to competing relaxation mechanisms

• Far away from single photon source