Photon Emission from a Cavity-Coupled Double Quantum Dot

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We study a voltage biased InAs double quantum dot (DQD) that is coupled to a superconducting transmission line resonator. Inelastic tunneling in the DQD is mediated by electron phonon coupling and coupling to the cavity mode. We show that electronic transport through the DQD leads to photon emission from the cavity at a rate of 10 MHz. With a small cavity drive field, we observe a gain of up to 15 in the cavity transmission. Our results are analyzed in the context of existing theoretical models and suggest that it may be necessary to account for inelastic tunneling processes that proceed via simultaneous emission of a phonon and a photon.

Cavity quantum electrodynamics (cavity-QED) explores quantum optics at the most basic level of a single photon interacting with a single atom [1]. One of the most important applications of quantum optics is the laser, in which population inversion of an atomic system provides an optical gain medium via stimulated emission. In cavity-QED, lasing has been achieved for single Rydberg atoms passing through a superconducting microwave cavity [2], and a single Ca atom strongly coupled to a high finesse optical cavity [3]. In this single atom limit novel effects were observed, including thresholdless lasing and antibunching of the emitted photons. Lasing has also been achieved in a solid-state device using a quantum dot emitter as a single ‘artificial atom’ inside a micropillar cavity [4].

Circuit quantum electrodynamics (cQED) exploits high quality factor superconducting resonators to realize strong coupling between microwave photons and a solid-state quantum device [5]. For superconducting qubits, the resonator enables qubit state readout and non-local qubit entanglement [6, 7]. In turn, superconducting qubits can be used to program non-classical photon states within the cavity [8–10]. Experiments have also used microwave cavities to explore photon emission from voltage-biased superconducting circuits [11, 12]. More recently, quantum dots have been integrated with superconducting microwave cavities, with large charge-cavity couplings $g_0/2\pi \sim 20 - 100$ MHz [13–17]. Spin-state readout [13, 14] and non-local coupling of distant quantum dot circuits [15] have also been demonstrated.

It is well known that electron tunneling in semiconductor DQDs can be driven by the absorption of microwave photons in a process called photon assisted tunneling (PAT) [18–21]. In this Letter, we investigate the inverse process, and show that dc transport of electrons leads to photon emission in a cavity-coupled InAs nanowire DQD. Previous work on semiconductor DQDs showed that inelastic interdot tunneling processes are mediated by spontaneous emission of a phonon [22, 23]. In our system, a charge-cavity coupling rate $g_0/2\pi \sim 16$ MHz opens up an additional channel for dissipation. Remarkably, we observe a gain of up to 15 in cavity transmission near the interdot charge transition with a device current $I \sim 8$ nA. Additionally, in the absence of a cavity drive, we directly measure a photon emission rate $\Delta \Gamma_p \sim 10$ MHz. Our experimental results show that the cavity-coupled DQD provides fertile ground for studying quantum optical effects in condensed matter systems [24].

Figure 1: (a) Optical micrograph of the hybrid system. Inset: Scanning electron micrograph of an InAs nanowire DQD. (b) The DQD is formed by biasing gates $B_L$, $B_R$ and $C$ at negative voltages to form left and right tunnel barriers with rates $\Gamma_L$ and $\Gamma_R$, and an interdot tunnel barrier with rate $\Gamma_c/h$. Cavity photons are coupled to the input and output ports with rates $\kappa_{in}$ and $\kappa_{out}$. A source-drain bias $V_{SD} = (\mu_D - \mu_S)/e$ is applied to the device. (c) Schematic of the charge stability diagram near the $(M, N+1)\leftrightarrow(M+1, N)$ interdot charge transition. Sequential tunneling is allowed within FBTs in the charge stability diagram (grey triangles). Inset: DQD energy level configuration in the lower FBT.
The hybrid device is shown in Fig. 1(a). A half-wavelength superconducting Nb transmission line resonator has a center frequency \( f_0 = 7862 \text{ MHz} \) and quality factor \( Q \sim 3600 \). Five Ti/Au bottom gates \( (B_L, L, C, R, B_R) \) selectively deplete an InAs nanowire resulting in a double well confinement potential, as shown in Fig. 1(b) [23, 26]. An excess charge trapped in the DQD interacts with the electric field of the resonator leading to a charge-cavity coupling rate \( g_0/2\pi \sim 16 \text{ MHz} \) [15, 27]. The device is measured in a dilution refrigerator with a base temperature of 8 mK.

With a source-drain bias applied across the DQD, sequential tunneling is allowed within finite bias triangles (FBT) in the charge stability diagram, as schematically shown in Fig. 1(c) [21]. Our experiments are performed in the many-electron regime and we label the DQD charge states \( (N_L, N_R) \), where \( N_L(N_R) \) denote the number of electrons in the left (right) quantum dot. In the lower FBT, DQD transport follows the cycle \( (M, N) \rightarrow (M, N+1) \rightarrow (M+1, N) \rightarrow (M+1, N+1) \). In Fig. 2(a) we plot \( I \) as a function of \( V_L \) and \( V_R \) with \( V_{SD} = 2.5 \text{ mV} \), revealing the FBTs. Well outside of the FBTs, where \( I = 0 \), the DQD is deep in Coulomb blockade and the charge state is fixed. Large tunnel couplings to the leads results in some cotunneling current between the FBTs.

Electronic transport can be driven by the absorption of a photon in PAT [19, 20]. Here we measure cavity transmission in the presence of a source-drain bias to determine if electronic transport results in photon emission. We apply a microwave drive at \( f_0 = 7862 \text{ MHz} \) with a power \( P \approx -105 \text{ dBm} \) and measure the amplitude \( A \) of the transmitted field using heterodyne detection [27]. Cavity transmission \( |A|^2 \) is plotted as a function of \( V_L \) and \( V_R \) in Fig. 2(b). The cavity transmission is normalized relative to the value measured deep in Coulomb blockade, where the DQD is effectively decoupled from the cavity [15]. Cavity transmission is reduced at charge transitions that change the total electron number, consistent with previous work [13, 15]. However, in contrast with previous work, we observe gain \( |A|^2 > 1 \) along the positive detuning side of the interdot charge transition where electron transport proceeds downhill in energy \( (\epsilon < 0, \Gamma_D > 0) \), indicating that photon emission is related to the \((M+1, N) \leftrightarrow (M, N+1)\) interdot charge transition.

The detuning dependence of the cavity transmission is investigated in Fig. 2(d) for \( V_{SD} = 0 \) (upper panel) and \( V_{SD} = 2.5 \text{ mV} \) (lower panel). For \( V_{SD} = 0 \), \( |A|^2 \) is reduced near \( \epsilon = 0 \), consistent with previous work [15]. In comparison, the data acquired with \( V_{SD} = 2.5 \text{ mV} \) show gain \( |A|^2 > 1 \) for \( \epsilon > 0 \) and a damping \( |A|^2 < 1 \) for \( \epsilon < 0 \). The gain that is observed for \( \epsilon > 0 \) indicates that the DQD is transferring energy to the cavity mode during the downhill inelastic interdot tunneling process.

Qualitatively, the DQD can be modeled as a charge qubit with Hamiltonian \( H = \frac{\epsilon}{2} \sigma_z + t_c \sigma_x \), where \( \sigma_x \) and \( \sigma_z \) are the Pauli matrices. This Hamiltonian results in a detuning dependent energy splitting \( \Omega(\epsilon) = \sqrt{\epsilon^2 + 4t_c^2} \). From conservation of energy, we anticipate strong emission into the cavity when \( h f_0 = \Omega \approx 33 \mu\text{eV} \). With \( \tau_c = 16.4 \mu\text{eV} \), this corresponds to \( \epsilon \approx 1 \mu\text{eV} \). Near \( \epsilon = 0 \) \( \mu\text{eV} \) we expect elastic tunneling processes to dominate [23], while at far detuning the effective charge-cavity interaction rate \( g = g_0 \frac{2 \pi}{\Omega} \) vanishes [15, 28–30]. We therefore expect photon gain effects to be the strongest for \( 0 \lesssim \epsilon \lesssim 30 \mu\text{eV} \). However, we observe a peak in transmission at \( \epsilon \approx 80 \mu\text{eV} \). Similarly, photon absorption should be the strongest for \( -30 \lesssim \epsilon \lesssim 0 \mu\text{eV} \). Surprisingly, microwave amplification and absorption both extend over a range of about \( 200 \mu\text{eV} \) range of detuning.

We model the zero-bias transmission data using the Jaynes-Cummings Hamiltonian with an effective charge-cavity interaction rate \( g = g_0 \frac{2 \pi}{\Omega} \) and coupling to a single dominant resonator mode of frequency \( f_0 = 7862 \text{ MHz} \) with a total decay rate \( \kappa/2\pi = f_0/Q = (\kappa_{in} + \kappa_{out} + \kappa_i)/2\pi \approx 2 \text{ MHz} \). We assume the cavity is symmetric with \( \kappa_{in} = \kappa_{out} \), and neglect internal
loss ($\kappa_i = 0$). Low frequency charge noise is accounted for by smoothing the fit function using a Gaussian with standard deviation $\sigma = 25 \mu eV$ [15]. As shown in Fig. 2(d), the model is in excellent agreement with the zero-bias data, yielding best fit values of $t_c = 16.4 \mu eV$ and $g_0/2\pi = 16 MHz$.

To model the sequential tunneling dynamics in the lower FBT, we consider a transport process proposed by Jin et al. that “repumps” the DQD into the excited state $(M, N+1)$ [27, 42]. A complete transport cycle is shown in the level diagram in Fig. 2(c). The DQD is pumped via a two-step incoherent tunneling process $(M+1, N) \rightarrow (M, N) \rightarrow (M, N+1)$ with rates $\Gamma_L$ and $\Gamma_R$, respectively. At far detuning, these two processes are equivalent to pumping from $(M+1, N)$ to $(M, N+1)$ with an effective pump rate $\Gamma_{\text{eff}} = \Gamma_R \Gamma_L / (\Gamma_R + \Gamma_L)$ if the dwell time in $(M, N)$ is short enough to be neglected. In the absence of other decay mechanisms, such as phonons, the electron tunnels from $(M, N+1)$ to $(M+1, N)$ by emitting a photon into the cavity mode to complete the transport cycle.

In terms of electron transport, our system is similar to the voltage biased Cooper pair box, where the voltage bias generates population inversion, producing a lasing state within the cavity [11]. Population inversion is achieved through a cycle that changes the relative number of Cooper pairs on the island by 1. Enhanced photon emission observed in cavity-coupled Josephson junctions has also been associated with Cooper pair tunneling events [12] and recently investigated theoretically [33, 54]. While there are similarities between the superconducting and semiconductor systems, the electron-electron interaction is known to strongly influence charge and spin dynamics in semiconductor DQDs leading to complex behavior [21, 23, 35, 36].

Predictions from the three-level model for $V_{SD} = 2.5 mV$ are shown in the lower panel of Fig. 2(d) [27]. Values of $\kappa, \gamma, t_c$ and $g_0$ are constrained by the $V_{SD} = 0$ data set. As before, the amplitude response function is smoothed using a Gaussian with width $\sigma = 25 \mu eV$ to account for charge noise. Taking $\Gamma_L = \Gamma_R$ as the only free parameters, the best fit has $\Gamma_L/2\pi = \Gamma_R/2\pi = 4 GHz$, in agreement with the values determined from the dc transport data [27]. The experimental data have gain that is 4 times larger than theory and the range of detuning over which gain is observed is 3 – 4 times broader in the experiments as well. Increasing the charge noise broadens the gain feature, but also reduces the level of gain, and is unable to account for the discrepancy.

The strong amplification and the broad linewidth in $\epsilon$ suggest that when the energy splitting of the DQD is 3–4 times the cavity energy, the system is still emitting photons effectively. Two potential contributions for this broadening include phonon-assisted and photon-assisted tunneling processes. Given previous work by Fujisawa et al. and Petta et al., it is known that phonon emission leads to charge relaxation rates on the order of 100 MHz [23, 31]. The charge relaxation rate is $\sim 6$ times faster than $g_0/2\pi = 16 MHz$ and competes with the charge-cavity coupling rate. One natural interpretation is that the DQD relaxes through emission of a phonon and a photon [33, 36]. A wider range of $\epsilon$ is then permitted for the resonant emission of photons. On the other hand, the large (8 nA) current through the device leads to a significant amount of shot noise with a high frequency cutoff $\omega_0 = \sqrt{\nu_{\text{sd}} \nu_{\text{sd}}}$ [37]. Thus in the region of high current flow, the additional noise may enable gain and loss processes to occur via a parametric coupling to the microwave resonator.

Stimulated emission is expected when the photon emission rate is strong enough to overcome cavity loss. To achieve higher photon emission rates we increased the tunnel coupling to the leads, resulting in an increase of the current through the DQD to $\sim 8$ nA [27]. Figure 3(a) shows $|\langle A \rangle|^2$ as a function of $V_L$ and $V_R$ with the device configured to have larger tunnel rates to the leads. ‘Hot spots’ with gain above 15 are observed. (b) $|\langle A \rangle|^2$ measured as a function of $f_R$ near a hot spot (green) and deep in Coulomb blockade (blue). Inset: The same data are plotted with normalized peak amplitudes. At the hot spot, the cavity linewidth is reduced by a factor of $\sim 3$.

![Figure 3](image-url)
searched for direct evidence of photon emission from the DQD in the absence of a cavity drive tone. The measurement setup is shown in Fig. 4(a). The output port of the cavity is connected to a high electron mobility transistor (HEMT) preamplifier and the resulting signal is detected using a microwave spectrum analyzer. The photon emission rate is plotted as a function of $V_G$ and $V_B$ in Fig. 4(b).

At the ‘hot spot’, we measure a photon emission rate $\Delta \Gamma_p \approx 10$ MHz above the background noise floor of the cryogenic HEMT amplifier (noise temperature $T_N = 4$ K). For a total cavity decay rate $\kappa/2\pi \approx 2$ MHz, the estimated photon number inside of the cavity is $N_p \approx 2\Delta \Gamma_p/\kappa \sim 2$ assuming the cavity is symmetric. We take this estimate of the photon number as a lower bound since it does not account for the internal loss of the cavity, and the line losses between the device and HEMT. We also note that $N_p$ is much higher than the thermal occupation number $1/[\exp(hf/k_B T) - 1] \ll 1$.

Our data strongly suggest that inelastic tunneling in the cavity-coupled DQD results in photon emission. Large cavity coupling rates in the cQED architecture lead to a new dissipation channel that competes with spontaneous emission of a phonon [23]. The photon emission efficiency $\beta$ can be estimated from the ratio of the photon emission rate to the electronic transport rate. The electron current $I$ at the ‘hot spot’ is $\sim 8$ nA and thus $\beta \geq 2\Delta \Gamma_p/(I/e) \sim 0.4 \times 10^{-3}$. This result should be contrasted with the Cooper pair box system, where photon emission is dominant and the efficiency is much closer to unity $\beta > 0.4$ [11]. The low efficiency of our cavity-coupled DQD suggests that other decay channels are stronger than photon emission and may explain why the emission of microwave photons has not been previously observed in semiconductor quantum dots.

In summary, we have investigated interactions between the dipole moment of a single excess electron in a DQD and the electromagnetic field of a microwave cavity. We observe a gain as large as 15 in the cavity transmission and also directly observe photon emission with a rate of 10 MHz above the noise floor of the HEMT amplifier. The gain observed in the cavity transmission is correlated with the interdot tunneling process, suggesting that inelastic current flow can proceed via emission of a photon or a phonon. Future experiments will explore the emission spectrum [11] and quantum statistics of the output photon field [3, 10, 29, 38]. Through further improvements in the photon emission efficiency, it may be possible to demonstrate novel microwave amplifiers or on-demand single photon sources through single electron pumping in the DQD.

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