Single electron-phonon interaction in a suspended quantum dot phonon cavity

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An electron-phonon cavity consisting of a quantum dot embedded in a free-standing GaAs/AlGaAs membrane is characterized in Coulomb blockade measurements at low temperatures. We find a complete suppression of single electron tunneling around zero bias leading to the formation of an energy gap in the transport spectrum. The observed effect is induced by the excitation of a localized phonon mode confined in the cavity. This phonon blockade of transport is lifted at resonance with the quantum dot. According to their calculations characteristic conductance resonances can be attributed to this effect have been observed for single electrons tunneling onto a C\textsubscript{60} molecule by Park et al.\textsuperscript{[15, 16]} The underlying physics of coherently coupling discrete electronic states with discrete phonon modes bears resemblance to cavity QED\textsuperscript{[21]}. A phonon cavity containing a suspended single quantum dot is shown in Fig. 1(a). The scanning electron micrograph was taken under an angle of 65° in order to visualize the three-dimensional character of the sample. Depicted in blue is the free-standing 130 nm thick GaAs/AlGaAs membrane containing a confined electron gas which is located 40 nm below the sample surface. The 400 nm thick sacrificial layer of Al\textsubscript{0.8}Ga\textsubscript{0.2}As supporting the membrane has been completely removed beneath the displayed part of the sample in Fig. 1(a) creating a spacing between the membrane and the GaAs buffer displayed in grey. The quantum dot is defined in a 600 nm wide bar by two point contacts formed by pairs of symmetric indentations. As a result of edge depletion the cavity has a reduced electronic diameter of about 450 nm. The two constrictions are wide enough to allow ballistic transport through the cavity, but can be depleted to form tunneling barriers by a nearby gate electrode. In the case of Fig. 1(a) this task is accomplished by a close-by Hall-bar being employed as an in-plane gate. A schematic top-view of the sample layout is displayed in the inset.

The presented measurements are performed in a dilution refrigerator with a base temperature of T\textsubscript{bath} = 10 mK. A negative voltage V\textsubscript{g} is applied to the gate electrode (i.e. the Hall-bar in Fig. 1(a)) in order to create tunneling barriers and to vary the electrochemical potential of the dot denoted \( \mu(N+1) = E(N+1) - E(N) \) in the level diagrams of Fig. 1(b) which will be discussed in more detail below. A bias voltage V\textsubscript{sd} can be applied between the source and drain reservoirs. The differential conductance \( G = dI_{sd}/dV_{sd} \) is recorded with respect

When Rolf Landauer discussed the importance of irreversibility and heat generation for classical transistors in 1961\textsuperscript{[1]}, he found that the minimal amount of dissipation required to perform a single bit operation is given by \( k_B T \ln 2 \). In the context of quantum physics the role of dissipation needs to be reconsidered. Even more, along with the discovery of single electron transistors\textsuperscript{[2, 3]} and quantum dots\textsuperscript{[4, 5]}, it is nowadays regarded as crucial for the feasibility of quantum computation\textsuperscript{[6, 7]}. The relevance of the electron-phonon interaction for quantum dot systems was initially theoretically confirmed by Brandes and Kramer\textsuperscript{[13]} and experimentally confirmed by Brandes et al.\textsuperscript{[17]}, pointing out the possibility to control electron dephasing by tailoring the phonon spectrum.

Here we report on the experimental observation of a new blocking mechanism of single electron transport which is found in such a cavity, evidencing the coherent interplay between single electron tunneling and the excitation of localized phonon modes confined in the cavity as predicted by Duke et al.\textsuperscript{[14]}. Strikingly similar features which can be attributed to the same effect have been observed for single electrons tunneling onto a C\textsubscript{60} molecule by Park et al.\textsuperscript{[15, 16]} The underlying physics of coherently coupling discrete electronic states with discrete phonon modes bears resemblance to cavity QED\textsuperscript{[21]}.
FIG. 1: (a) Suspended quantum dot cavity and Hall-bar formed in the blue-colored 130 nm thin GaAs/AlGaAs membrane. The inset shows a schematic top view of the sample. (b) Level diagrams for single electron tunneling including phonon blockade: (i) In the orthodox model electrons sequentially tunnel through the dot, if the chemical potential \( \mu(N + 1) \) is aligned between the reservoirs. (ii) Tunneling into the phonon cavity results in the excitation of a cavity phonon with energy \( \hbar \Omega_{ph} \), leading to a level mismatch \( \epsilon_0 \) and thus to phonon blockade. (iii) Single electron tunneling is re-established by a higher lying electronic state \( \mu^*(N + 1) \) which is enabled to coherently reabsorb the phonon and to hereby replace the ground state \( \mu^0 \).

These results can be compared to recent theoretical models for transport through a molecular single electron transistor coupled to a single vibrational mode \( \Omega \) \cite{22, 24}. We have extended these models \( \Omega \) in order to analyze the origin of the observed blockade mechanism. The picture corresponding to the classical limit (strongly overdamped vibration mode) is illustrated in Fig. 1(b): (i) In case of a conventional single electron transistor an electron sequentially tunnels through a non-suspended quantum dot whenever Coulomb blockade can be overcome, i.e., the electrochemical potentials of source, drain, and the dot \( \mu_S, \mu_D \) and \( \mu(N + 1) \) are aligned. This situation corresponds to the well-known Mössbauer-effect \( \Omega \) in gamma spectroscopy: Recoil-free absorption and emission of gamma-ray photons is enabled for a nucleus being placed in a solid since the crystal takes up the recoil as a whole without entailing an energy loss. In a classical picture this is equivalent to the reflection of a particle at a hard wall with infinite mass. (ii) This behavior changes dramatically for a quantum dot embedded in a suspended phonon cavity a classical analogue of which is given by a particle hitting a trampoline. Due to strong electron-phonon coupling in the cavity \( \Omega \) (see below), single electron tunneling induces mechanical displacement of the suspended quantum dot which corresponds to the excitation of a localized cavity phonon of energy \( \hbar \Omega_{ph} \). Flensberg has shown \( \Omega \) that in the strongly overdamped, classical limit (quality factor \( Q = \Omega_{ph}/\gamma \ll 1 \) for small phonon life time \( \gamma^{-1} \)), the energy cost of the displacement goes along with a drop of the chemical potential \( \mu(N + 1) \) in the dot, which leads to a blockade of single electron tunneling. The energy gap \( \epsilon_0 = g \hbar \Omega_{ph} \) then depends on the Franck-Condon coupling constant \( g \). In the ‘Mössbauer picture’ \( \Omega \), the cavity picks up the ‘recoil’ of the tunneling electron and immediately relaxes to a new ground state for \( Q \rightarrow 0 \). On the other hand, \( Q \rightarrow \infty \) would correspond to coherent cavity phonons where the Franck-Condon factors yield a series of phonon side-bands \( n \Omega \) with weights given by the Poisson distribution \( e^{-g \hbar \Omega / n!} \) at zero temperature with \( n = 0 \) corresponding to elastic tunneling.

To re-establish single electron tunneling, the energy transferred to the cavity can be regained as displayed in part (iii) of Fig. 1(b) where the cavity phonon is reabsorbed exciting a higher lying electronic state \( \mu^*(N + 1) \). To this end, the excited cavity phonon mode coherently exchanges energy with the electronic excited states \( \mu^*(N + 1) \) which can be understood in terms of (damped) Rabi oscillations \( \Omega \).

An estimate for the phonon modes and energies confined to the quantum dot cavity is obtained from microscopic calculations \( \Omega \) that find van-Hove singularities in the cavity phonon density of states, accompanied by an extreme enhancement of phonon emission at certain phonon energies. The lowest energy where this occurs is \( \hbar \Omega_{ph} \approx 3h \epsilon_1 / z = 73 \mu eV \) for quantized dilatational
photon modes ($\hbar \Omega_{ph} \approx 145 \mu eV$ for flexural modes) for the sample thickness $z = 130$ nm and the longitudinal velocity of sound in the $[100]$ direction of bulk GaAs, $c_l = 4.77 \cdot 10^5$ cm/s. This prediction for $\hbar \Omega_{ph}$, based on a simple infinite thin-plate model, compares relatively well to the observed energy gap $\epsilon = 100 \mu eV$ found in our transport data at an electron temperature of 100 mK.

At larger temperatures the electrons gain enough energy to overcome phonon blockade when the broadening of the Fermi distribution function suppling empty states in the reservoirs.

The phonon gap $\epsilon$ is recorded with a higher resolution in Fig. 2(a) showing the central region of Fig. 2(a) in the same color scale. The conventional shape of the Coulomb diamonds is marked by solid lines. Clearly, the asymmetric shape of the gap can be discerned: The crossing of the two solid lines indicates the position of the missing single electron tunneling conductance peak. The onset of conductance gap. Energetically higher lying electronic states $\mu^*(N+1)$ with finite angular momentum $\ell \cdot h$ ($\ell = 1, 2, ...$) can be brought into resonance with the cavity phonon by altering the magnetic field such that the excitation energy $\mu^*(N+1, B) - \mu(N+1, B = 0) = \epsilon_0$, corresponding to the situation displayed in level diagram (iii) of Fig. 1(b). In this case, the higher states offer a broad cross section for the emitted phonons to be reabsorbed, allowing for the excitation of the electron into $\mu^*(N+1)$ thus enabling it to sustain single electron tunneling. Examples for such resonances can be seen at 170 mT and 450 mT shown in Fig. 3(b) and (d) whereas a non-resonant situation at 260 mT is displayed in Fig. 3(c). Since reabsorption of the phonon only occurs with a finite probability, the height of the conductance peak at zero bias, which is again displayed in the right part of the figure, is reduced compared to the onset of conductance through the original ground state at $V_{sd} = \epsilon/e$ marked by the dotted line as described before.

A direct comparison of the magnetic field dependence to transport spectroscopy on the dot is depicted in Fig. 4 where we consider two adjacent resonance peaks $\alpha$ (right, c.f. Fig. 3) and $\beta$ (left). The conductance traces are recorded for bias voltages from $0 \mu V$ to $-800 \mu V$ at $B = 0$ mT in Fig. 4(a) showing excited states marked by red lines. The zero bias conductance is plotted logarithmically as a function of both gate voltage $V_g$ and magnetic field $B$ for $\alpha$ and $\beta$ in Fig. 4(b) (blue: $0.02 \mu S$, red: $0.2 \mu S$) and (c) (blue: $0.02 \mu S$, red: $2 \mu S$), respectively. For the right resonance $\alpha$ we find excited states
The conductance at $V_{sd} = 0 \mu V$ is suppressed. (b) Zero bias conductance for resonance $\alpha$ plotted against gate voltage $V_g$ and magnetic field $B$. (c) Similar plot for resonance $\beta$ (blue: $0.02 \mu s$, red: $2 \mu s$): Non-zero conductance is found for $230 \text{ mT}$ and $510 \text{ mT}$.

For the left resonance $\alpha$, we find excited states at energies $\mu^1_\alpha = 230 \text{ meV}$, $\mu^2_\alpha = 440 \text{ meV}$, and $\mu^3_\alpha = 740 \text{ meV}$. These three excited states correspond to three magnetic fields permitting zero bias conductance at $57 \text{ mT}$, $170 \text{ mT}$, and $400 \text{ mT}$. For the left resonance $\beta$ we find excited states at energies $\mu^1_\beta = 380 \text{ meV}$ and $\mu^2_\beta = 760 \text{ meV}$ matching with two magnetic fields re-enabling zero bias conductance at $230 \text{ mT}$ and $510 \text{ mT}$. Above $500 \text{ mT}$ conductance fully re-emerges while below it is found only at a set of discrete values as discussed above. These values exactly correspond to multiples $B = n \cdot B_0$ ($n = 1, 3, 4, 7$ and $9$) of the first resonance in $\alpha$ observed at $B_0 = 57 \text{ mT}$.

The presented measurements demonstrate that for freely suspended quantum dot cavities single electron tunneling gives rise to the excitation of a longitudinal cavity phonon. The resulting energy loss leads to a suppression of linear electron transport and to the formation of a distinct energy gap. This phonon blockade effect can be overcome at bias voltages large enough to bridge the energy gap, or at a sufficiently high bath temperature. A third mechanism circumventing phonon blockade is given by aligning higher lying electronic states with distinct angular momentum such that electronic transport is enabled through these states after reabsorption of the cavity phonon in a process similar to Rabi oscillations. Finally, placing the dot into the whole bulk crystal instead of a free-standing cavity eliminates the blockade effect so that elastic single electron tunneling is restored.

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**FIG. 4:** (a) Line plot of conductance resonances $\alpha$ and $\beta$ at different source-drain bias voltages between $0 \mu V$ and $-800 \mu V$. Blue lines follow the ground states, while red lines mark excited states. The conductance at $V_{sd} = 0 \mu V$ is suppressed. (b) Zero bias conductance for resonance $\alpha$ plotted against gate voltage $V_g$ and magnetic field $B$. Finite conductance appears for $57 \text{ mT}$, $170 \text{ mT}$, and $400 \text{ mT}$. (c) Similar plot for resonance $\beta$ (blue: $0.02 \mu s$, red: $2 \mu s$): Non-zero conductance is found for $230 \text{ mT}$ and $510 \text{ mT}$.

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