Phonon-mediated back-action of a charge readout on a double quantum dot

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Abstract
Quantum point contacts are in use as an on-chip capacitative readout for the charge state of quantum dot systems. Here we investigate experimentally the back-action of quantum point contacts (QPCs) on a nearby double quantum dot (DQD). Driving current through a QPC influences the DQD state and leads to a measurable current flow in the DQD circuit with no bias voltage applied. The responsible mechanism is an indirect back-action process due to ohmic heating of the phonon bath. The system behaves like a thermoelectric engine, where a temperature gradient between the phonon bath and the electronic bath generates work observable as a measurable current flowing through the DQD.

1. Introduction
A semiconductor double quantum dot (DQD) [1] regarded as a two-level quantum system [2, 3] is a prospective candidate for a charge qubit [4–7], a possible building block of future quantum information processors. It can be controlled and manipulated by electronic signals. On-chip integration of a DQD with a quantum point contact allowed us to readout the charge state of the DQD [8–12]. However, on-chip detectors can cause decoherence of the qubit state [13–18]. In this paper we investigate experimentally indirect back-action of the quantum point contact on the double quantum dot via ohmic heating of the phonon bath. We show that such a system can be considered as a thermoelectric generator.

The outline of this paper is as follows. In section 2 we describe the DQD as a two-level system and introduce the concept of charge detection. Then we discuss the relevant back-action mechanisms. The sample used in this experiment is characterized in section 3. Section 4 presents the measured data and the interpretation of the results based on electron-phonon coupling.

2. Background information
2.1. Double quantum dot as a two-level system
By definition, a double quantum dot consists of two single quantum dots [19] separated by a tunneling barrier as shown in figure 1(a). Changing the shape of the barrier is equivalent to changing the tunneling coupling $t$ between the quantum dots. In this way it is possible to tune the system smoothly from two single quantum dots (weak tunneling coupling) into a quantum dot molecule (strong tunneling coupling), as demonstrated in [20].

A quantum dot molecule can be described as a quantum mechanical two-level system [1]. Due to the finite tunneling...
coupling \( t \), the single-electron ground states of the left and the right dots \( (E_L \) and \( E_R \) hybridize and form molecular bonding (ground) and antibonding (excited) states as depicted in figure 1(b). The energy difference \( \Delta \) between the excited and ground state is \( E_R - E_A = \Delta = \sqrt{\delta + 4t^2} \), where the detuning \( \delta \) is the energy difference between the single-particle energy levels in the absence of tunneling coupling \( (t = 0) \), given by \( \delta = E_L - E_R \). In figure 1(b) the single-particle energies are equal \( (E_L = E_R) \). In this special case \( \delta = 0 \) and \( \Delta = t \).

The hallmark of solid-state quantum dots is the possibility to control energy states and the height of tunneling barriers via external voltage sources. Quantum molecules can be realized in many materials: in GaAs [1] and SiGe [21] heterostructures, semiconductor nanowires [22], carbon nanotubes [23] and graphene [24].

2.2. Integrated on-chip charge detectors

A quantum point contact (QPC) is a narrow ballistic constriction connecting two macroscopic electron reservoirs. The conductance \( G \) of a QPC is determined by the width of the channel. If it is very narrow, the current is pinched off and the conductance is zero. As the wire becomes wider, the conductance rapidly increases and then saturates, creating the first plateau at the conductance quantum \( G = 2e^2/h \).

In the vicinity of the point of maximum slope (around \( G = e^2/h \)) the conductance of a quantum point contact is extremely sensitive to tiny changes of the potential landscape. This allows for the use of a QPC as a non-invasive detector of the QD charge state [25]. The mechanism of detection relies on the Coulomb interaction between the capacitively coupled QD and QPC. Adding an electron to the QD results in a repulsive Coulomb potential that reduces the actual width of the constriction. This leads to a reduction of the conductance of the QPC.

This on-chip charge detection technique proved to be a useful tool for studying charge states in double quantum dots. Integrating a charge readout next to a DQD allows one to investigate an operating regime, where the current through the DQD is too small to be measured directly [9, 26].

The sensitivity of charge detection depends strongly on the geometric design and on the materials used. The bare Coulomb potential is inversely proportional to the distance between the probe and the detector. This limits the lateral size of dot–detector systems fabricated from semiconductor heterostructures. It is also possible to use systems where the DQD and the charge readout are aligned vertically [27], which leads to enhanced sensitivity compared to lateral devices. The presence of metallic top-gates screens the Coulomb potential, reducing the sensitivity of the detector.

2.3. Back-action mechanisms

The major difference between classical and quantum systems is that the former can be measured many times without destroying its state. This is not the case for a quantum system, where the measurement usually changes the quantum state [28]. This phenomenon is called quantum back-action.

![Figure 2](image-url)  

**Figure 2.** (a) Driving current through quantum point contacts leads to energy dissipation. This energy can be later absorbed by a double quantum dot. (b) AFM image of the sample. The oxide lines written on GaAs are white. The oxide lines on Ti are indicated by dashed lines. The sample consist of three electrical circuits containing double dot (dashed arrow) and two separated quantum point contacts (solid arrows). Tunability of the system is provided by in-plane gates (marked with white letters) and mutually isolated top gates (marked with black letters).

Back-action of a charge detector on the coupled quantum system leads to a quantum limit of detection. There are theoretical considerations showing that, under certain conditions, this limit can be reached [16]. To find this limit experimentally it is necessary to understand and reduce the influence of different mechanisms that contribute to back-action [29].

One of the methods to investigate back-action is to use the measured system as the detector, while the original detector serves as the probed system as shown in figure 2. A possible scheme is a double dot coupled capacitively to a quantum point contact [26, 30].

One mechanism of perturbing the DQD system by the QPC is direct coupling via shot noise [26]. The finite-frequency shot noise in a quantum point contact is generated when the bias voltage applied across the constriction is larger than the temperature of the leads. It results in emitted energy quanta that can be directly absorbed by the DQD [26].

In this paper, we focus on an indirect back-action via ohmic heating of the phonon bath. To eliminate the effect of the shot noise, the measurements described below are performed with the QPCs’ operating point set to the first conductance plateau. At this point the power spectral density of the QPCs shot noise is close to zero. Additional screening of the Coulomb coupling is provided by metallic top-gates covering the entire structure. In this regime, the energy generated by driving a current through a quantum point contact is predominantly absorbed by the phonon bath. Later, part of this energy is transferred into work driving current in the DQD via electron–phonon interaction, as we will show below.

3. Fabrication and characterization of the sample

The sample used in the experiment is based on a GaAs/AlGaAs heterostructure with a two-dimensional electron gas 34 nm below the surface. It was fabricated by double-layer local anodic oxidation described in detail in [31].

In the first step the oxidation was performed directly on GaAs. The two-dimensional electron gas is depleted below the oxide lines, creating electrically isolated circuits. Using this method, three mutually isolated electrical circuits shown in
function of in-plane gates ipg1 and ipg2 (see figure 2(b)). In this measurement both QPCs are pinched off. In this regime, each of the dots contains an estimated number of 15 electrons. The charging energies for both dots are about 2 meV. The boundaries of the characteristic honeycomb pattern [33, 1] are marked by dashed lines, whereas \((M, N)\) number the electrons in the left and the right dot, respectively. The coupling between the left dot and the source lead is stronger than the coupling between the right dot and the drain contact, as can be seen by the strength of the co-tunneling lines.

Figure 4 presents the conductances through QPC1 and QPC2 as a function of top-gate voltages. In the experiment, the operating point was set at the first plateau for both QPCs (see arrows) to suppress the shot-noise contribution.

4. Phonon-mediated electron transport through a DQD

4.1. Experimental manifestation

The effect of the QPC on the DQD is illustrated in figure 3(b). The color code in the diagram presents the direct dc current through the DQD as in (a). In this measurement, a bias voltage of 1 mV was applied across QPC2. The bias voltage across the DQD was \(V_{SD} = 60 \mu\text{eV}\). Driving current through QPC2 results in lifting the Coulomb blockade in the DQD circuit as seen in the triangular region marked in red (dashed grey) in figure 3(b).

To investigate this effect in more detail, we focus on the detuning line marked in red (dashed grey) in figure 3(a). Sweeping the gates along the detuning line corresponds to tuning the energy difference \(\Delta\) without changing the average energy of the two levels. First, the bias voltage across the DQD and both of the QPCs is set to zero. The result is shown in figure 5(a) (black squares). There is no current flowing through the DQD. The situation changes if we drive current through one of the QPCs. At zero detuning, there is no net current flowing through the DQD, as seen in figure 5(a) (colored squares). As the detuning is increased, the DQD current increases, then reaches its maximum and decays slowly. The situation is analogous for negative detuning, for which the effect is less pronounced due to asymmetric coupling of the DQD to the leads. In general, the higher the current through the QPC, the stronger the observed response from the DQD. The magnitude of the induced DQD current is five orders of magnitude smaller...
than the QPC current. Comparison of figures 5(a) and (b) shows that QPC2 induces a stronger current in the DQD than QPC1. From that we conclude that QPC2 is stronger coupled to the DQD than QPC1. The strength of the coupling depends strongly on lithographic details. Small fluctuations of the width, height and the exact position of the GaAs oxide lines can influence the potential landscape and therefore affect the coupling between the QPC and the DQD. This experiment demonstrates that it is possible to measure a finite current through the double quantum dot at zero bias voltage. Driving current through a QPC nearby supplies the necessary energy and the detuning is the important parameter that is responsible for breaking the symmetry of the system.

Figure 6(a) shows the dependence of DQD current as a function of QPC current at a fixed detuning of $\delta = 200 \mu eV$. The black (red) filled squares correspond to positive currents through QPC1 (QPC2) swept from 0 to 200 nA. The empty black (red) circles are the traces recorded while QPC1 (QPC2) current was swept from 0 to $-200$ nA. The DQD response is slightly more pronounced when the QPCs are driven with positive current. We excluded the gating effect as the reason for this polarity dependence. This was done by calculating the change in the DQD potential using the lever arms of the in-plane gates. As observed before, QPC2 has a stronger influence on the DQD than QPC1. The filled (empty) green symbols correspond to the QPC1 current being swept from 0 to 200 ($-200$) nA while the QPC2 current is simultaneously swept from 0 to 200 nA. Driving both QPCs at the same time leads to a slight enhancement of the DQD current, compared to the traces when only the stronger coupled QPC2 is used. This shows that the effects of the independent QPCs do not add up but the process responsible for driving the current through the DQD has a more complex origin. The polarity dependence is also seen in these traces. The maximum DQD current is measured when the current in both QPCs flows in the positive direction. Figure 7(c) shows analogous data for the detuning fixed at $\delta = 100 \mu eV$. Here, the overall dependence stays the same, but the magnitude of the DQD current is significantly smaller.

4.2. Indirect back-action via ohmic heating of the phonon bath

The mechanism responsible for driving the DQD at zero bias voltage is presented in figure 2(a). The driving current through the QPCs leads to the emission of energy which can be absorbed by the electron in the right dot. Provided that the emitted energy matches the energy difference $\Delta E$ between the bonding and the antibonding state of the quantum dot molecule, the electron can be excited from the right to the left dot. Such an electron will most likely relax back to the ground state (with energy emission). Additionally, it can also
the electron to the excited state of the DQD entanglement is created between the phonon and the electron system. In other words, there is a back-action of the charge detector on the double quantum dot.

The detailed model describing the coupling between the DQD and the phonon bath is presented in [37]. In this model, the transitions between different charge states of the double quantum dot are described using a rate equation approach. The coupling of electrons in the DQD to acoustic phonons is considered using first-order perturbation theory. The acoustic phonons couple via piezoelectric coupling and a deformation potential. The model assumes, for simplicity, that the phonon bath is in equilibrium and can be described using an effective temperature $T_{ph}$. The electrons in the leads connected to the double quantum dot are assumed to be in equilibrium as well. They are characterized by the temperature $T_{el}$. The result of the model is an expression for the double quantum dot current. The most important fitting parameter is the temperature of the phonon bath $T_{ph}$.

Here, we focus on the different contributions that lead to the observed $\delta$ dependence of the DQD current. The response of the DQD to the finite QPC current as a function of detuning was shown in figure 5. All these traces have common features. At zero detuning, there is no current flowing through the DQD. As the detuning is increased, the dot current rises fast, and after reaching the maximum it decays slowly. The key parameters in the expression for the total DQD current are transition rates for emission and absorption of an energy quantum in the DQD. Their dependence on the energy splitting $\Delta$ is

$$
\Gamma_{em/abs} = \sum_{\lambda} C(\Delta) F(\Delta) S_\lambda(\Delta).
$$

These rates are obtained using Fermi’s golden rule including the double quantum dot energy levels, geometry, electron–phonon coupling and the energy distribution of the phonon bath. The index $\lambda$ denotes the piezoelectric transversal phonons ($\lambda = (pe, T)$), piezoelectric longitudinal phonons ($\lambda = (pe, L)$) and longitudinal deformation potential coupling ($\lambda = (dp, L)$). The upper (lower) sign stands for emission (absorption) of energy quanta. In the following, we discuss the energy dependence of each term in expression (1) and its influence on the overall shape of the measured data.

The first term in equation (1) can be written as $C(\Delta) = \gamma_e \Delta e^w$. It contains the energy-independent electron–phonon coupling constant $\gamma_e$. In the remaining part $n_{dp}$ is equal to zero for deformation potential coupling and $n_{pe} = -2$ for piezoelectric coupling.

The form factors that enter equation (1) are gathered together in the function $F(\Delta)$. Here, the low-energy increase in emission and absorption rates originates from the influence of the double-dot geometry and the separation of the single dots in the double-dot system. The separation suppresses small energy absorption for phonon wavelengths much larger than the distance $d$ between the dots, as shown schematically in figure 9. One of the form factors contributing to the high-energy cutoff of the DQD current arises from the symmetry of the double quantum dot wavefunction. This factor suppresses transitions for the asymmetric system. For large detuning it is
The excitation of an electron in a double quantum dot is weak if the wavelength of the phonon is much larger than the distance between the dots. (b) If the wavelength of the phonon is comparable to the distance between the dots, it is easier to excite the electron.

The last term in equation (1) represents the phonon power spectral density $S_\delta(\Delta) = \Delta D(\Delta)[n_0(\Delta, T_{ph}) + 1/2 \mp 1/2]$. It increases with energy due to the phonon density of states, which is proportional to $\Delta^2$. This contribution leads to more phonons at higher energies. The high-energy cutoff is caused by the Bose–Einstein distribution function $n_0$ describing the occupation of a phonon bath. It slowly decays at higher energies, where it is proportional to $\exp(-\Delta / T_{ph})$.

As mentioned before, at zero detuning there is no current flowing through the device. At this particular point, the system is symmetric, and the absorption and emission processes are still present, but there is no preferred direction. On average, the same amount of electrons flows in the right and the left direction carrying zero net current. As soon as the symmetry of the system is broken by increasing the detuning, the net current through the DQD increases and, after reaching its maximum, it decays slowly. The $\delta$-dependent phonon power spectral density $S_\delta(\Delta)$ cannot be measured directly, because it is convoluted with the form factors $F(\Delta)$, as shown in equation (1). Both of them have low-energy increase and the high-energy cutoff appearing at similar energies. This is in contrast to the experiments probing the shot-noise spectral density [26].

The model described above gives a detailed qualitative understanding of the measured data. Moreover, it can also be used to extract the experimental parameters that cannot be measured directly, such as the temperature of the phonon bath $T_{ph}$. The solid lines in figure 5 are fits of the model to the data. The temperature of the phonon bath $T_B$ extracted from the fits changes from 0.6 K (blue trace in figure 5(a)) to 1.2 K (red trace in figure 5(b)). The difference between the temperatures $T_{ph}$ and the electronic temperature $T_e = 100$ mK provides the necessary energy to drive the current through the DQD.

Figure 6(b) presents the temperature of the phonon bath $T_{ph}$ extracted from the fits as a function of the QPC currents. These temperatures were calculated for every point shown in figure 6(b). The dependence is quadratic, $T_B \sim I_{QPC}^2$, which indicates that the temperature of the bosonic bath is proportional to the power emitted by the QPC. The same procedure was applied to extract the temperatures from figures 7(a) and (c). The result is shown in (b) and (d). For small DQD current it is difficult to estimate $T_{ph}$ with sufficient accuracy.

To demonstrate how well the model describes the measured data we plot the calculated current through the DQD as a function of the gate voltages in the absence of the QPC current and in the case where QPC is biased with 1 mV (which gives $T_{ph}$ around 0.8 K). The results are shown in figures 3(c) and (d). The first one should be compared with the measured data in figure 3(a), whereas the second is corresponding to (b). The qualitative and quantitative agreement of the data and model are reasonable.

The important differences between the experiment described here and the experiments aiming at measuring the direct back-action via shot noise originating from the quantum charge readout [26] are the following. First, in this experiment, the direct current through the DQD was measured, so the coupling of the DQD to the source and the drain contacts was many orders of magnitude higher than in time-resolved experiments. Second, shot noise is expected to be suppressed, since the QPCs were operated at the first conductance plateaus. Additionally, metallic top gates efficiently screen Coulomb interactions, further reducing the electrostatic coupling between the DQD and the QPSs. Also the quantum point contacts were biased with much higher voltages (up to 1 mV) than in the experiments reported in [26].

The current polarity effect remains unexplained within the framework of the electron–phonon interaction model. One could study this effect for simpler lateral geometries, for example, with a lateral QCD coupled capacitively to a QPC aligned along the DQD circuit. This experiment could be performed for different crystallographic orientations. Another point worth further study is the strength of the interactions as a function of the DQD–QPC separation.

5. Conclusions

In the regime where electrostatic coupling between the double quantum dot and the quantum point contacts is suppressed, electron–phonon interactions can play the dominant role. Indirect coupling of the QPC to the DQD is mediated by phonons in the host crystal. The phonon bath is heated up by the current flow through the QPC. The difference between the electronic and phononic temperatures provides the necessary energy to overcome the energy gap (determined by the detuning $\Delta$) and drives the current through the double quantum dot. This phonon-mediated back-action of the QPC is significant and the system acts as a thermoelectric engine.

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