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Dynamic Rabi oscillations in a quantum dot embedded in a nanobridge in the presence of surface acoustic waves

L Mourokh¹, A Wixforth², F Beil³, M Bichler⁴, W Wegscheider⁵ and R H Blick⁶

¹Physics Department, Queens College of CUNY, Queens, NY 11367, USA

²Physics Department, University of Augsburg, Universitätsstr. 1, 86159 Augsburg, Germany

³Ludwigs-Maximilians-Universität-München, Geschwister-Scholl-Platz 1, 80539 München, Germany

⁴Walter-Schottky-Institute, Am Coloumbwall 3, 85748 Garching, Germany

⁵Laboratory for Solid State Physics, HPF E 7, ETH Zurich, Schafmattstrasse 16, 8093 Zurich, Switzerland

⁶Center for Hybrid Nanostructures (CHyN) and Institutes of Nanostructure and Solid State Physics, University of Hamburg, Lurupuer Chaussee 149, 22761 Hamburg, Germany

lev.murokh@qc.cuny.edu

Abstract. A quantum dot is created within a suspended nanobridge containing a two-dimensional electron gas. The electron current through this dot exhibits well-pronounced Coulomb blockade oscillations. When surface acoustic waves (SAW) are driven through the nanobridge, Coulomb blockade peaks are shifted. To explain this feature, we derive the expressions for the quantum dot level populations and electron currents through these levels and show that SAW-induced Rabi oscillations lead to the observed phenomenology.

1. Introduction

As modern electronic devices become smaller, it is compulsory to investigate possible quantum effects, which emerge due to the electron confinement [1]. In Nano-Electromechanical Systems (NEMS), it is also important to examine how the actual mechanical motion at the nanoscale affects the electrical properties of the structure [2]. The interplay between the electron confinement and nanomechanics is hence of special interest.

Surface acoustic waves (SAWs) are perfectly suited to provide an excitation mechanism for suspended nano-structures [3]. SAWs are acoustic modes propagating at the surface of an elastic solid, having wavelengths in the range of some microns and penetration depths of the same order. Excitation of SAWs at a specific frequency is in particular effective employing a piezoelectric substrate (GaAs in our case) and properly designed interdigitated transducers (IDTs). As typical SAW amplitudes can be in the range of nanometers, they effectively modulate the acoustic properties of nanomechanical devices.



2. Sample preparation and experimental results

For sample preparation, we use nanomachined AlGaAs/GaAs-heterostructures including a two-dimensional electron gas, which is grown on a sacrificial layer. Additionally, indentations are used to introduce the lateral confinement, i.e. to form a quantum dot (see Fig. 1). Upon removal of the sacrificial layer, so-called phonon cavities are realized containing the low-dimensional electron system. An additional gate is located above the nanobridge to control the energy levels of the quantum dot. The details of this structure are shown in Fig. 1(a).

We measure the electron current through the system as a function of gate voltage and obtain well-defined Coulomb blockade peaks, as shown Fig. 1(b), confirming the formation of a quantum dot. These measurements are executed at the lattice temperature of 25 mK with an elevated electron temperature of ~ 100 mK.

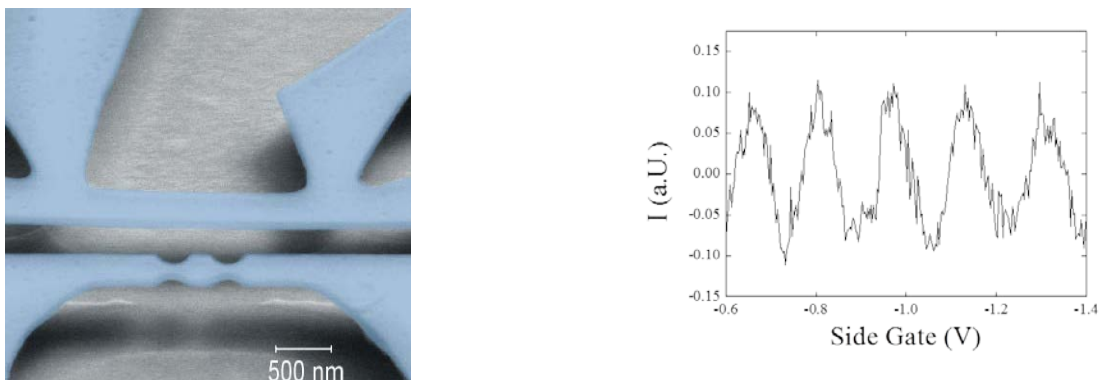


Figure 1. Left: The device under study showing the suspended nanobridge, which contains a 2DEG with the quantum dot defined by the two constrictions left and right. The additional suspended bridge next to the quantum dot is employed as gating electrode for controlling the quantum dot's energy levels. **Right:** Coulomb blockade peaks indicating the single-electron transfer events.

When the beam is subject to SAWs, the positions of the Coulomb blockade peaks are shifted as the power of SAW increases, see Fig. 2.

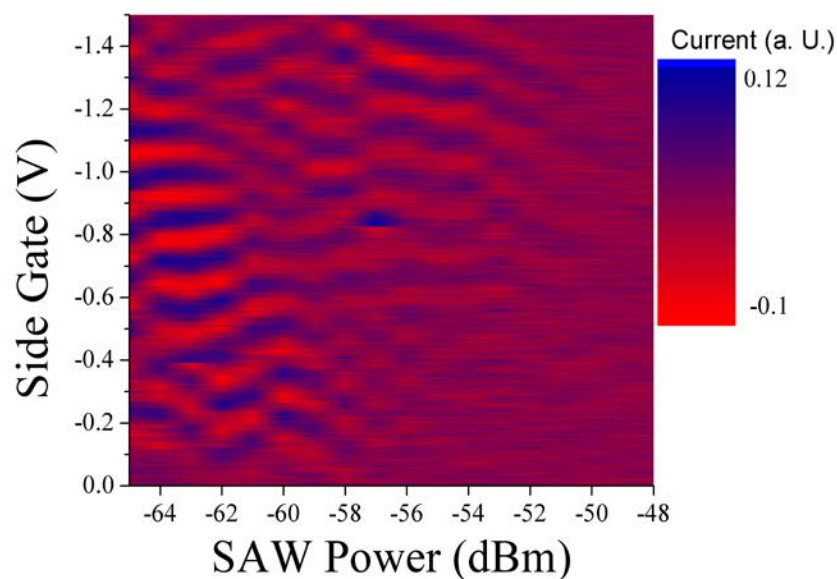


Figure 2. Current through the structure as a function of the side gate voltage and SAW power.

Two key effects were observed. At low SAW power, the positions of the Coulomb blockade peaks are shifted, while at high power the Coulomb blockade is mainly lifted. We attribute the latter effect to the electron heating and will discuss the former one in the next Section.

3. Theoretical approach and discussions

To describe the effect of SAW on electron transport through a quantum dot embedded in a nanobeam, we introduce a term in the Hamiltonian accounting for the motion of the clamping points of the nanobridge. This motion produces a periodic strain ε_{ij} in the beam. Because of a piezoelectric interaction, characterized by the tensor Ξ_{ij} , this strain induces the oscillations of the electron energy in the dot, $\Delta E = -F \sin(\Omega_0 t)$; where Ω_0 is the SAW frequency and F is the amplitude of energy oscillations, $F \sim \sum \varepsilon_{ij} \Xi_{ij}$. Even the moderate SAW amplitude of 0.1nm induces a strain of the order of $\varepsilon \sim 10^{-4}$, which, in turn, results in the amplitude of the energy oscillations of $F \sim 1meV$, if the electron-phonon constant is $\Xi_{ij} \sim 10eV$. It should be noted that our experiment is performed in the adiabatic regime, in contrast to that of Ref. [4], because the frequency of the SAW oscillations, Ω_0 , is much smaller than the charging energy of the dot, U , temperature, and the broadening of the electron levels inside the dot, $\Gamma \sim 10\mu eV$. However, the amplitude of the energy oscillations, F , can be comparable to the charging energy.

For simplicity, we examine only one spatial electron wavefunction in the dot, which can be occupied by the two electrons having opposite spin projections, and the corresponding energy levels are separated by the on-site Coulomb energy, U . With spatial level quantization being much smaller than U , other energy levels would be also separated approximately by U , as in well-known Coulomb blockade experiments, and our results can be easily extended. Correspondingly, the Hamiltonian of the system has the form

$$H = \sum_{\sigma=1,2} (E_{\sigma} + F(t)) a_{\sigma}^{\dagger} a_{\sigma} + U a_1^{\dagger} a_1 a_2^{\dagger} a_2 + \sum_{k,\sigma,\alpha=L,R} E_{k\alpha\sigma} c_{k\alpha\sigma}^{\dagger} c_{k\alpha\sigma} - \sum_{k,\sigma,\alpha} T_{k\alpha\sigma} c_{k\alpha\sigma}^{\dagger} a_{\sigma} - \sum_{k,\sigma,\alpha} T_{k\alpha\sigma}^* a_{\sigma}^{\dagger} c_{k\alpha\sigma}. \quad (1)$$

Here, $a_{\sigma}^{\dagger}/a_{\sigma}$ and $c_{k\alpha\sigma}^{\dagger}/c_{k\alpha\sigma}$ are the creation/annihilation operators in the dot and in the α -lead. Using the approach developed in Ref. [5], for the steady state (slowly varying in time with the driving force $F(t)$), we obtain the following equations for the level populations

$$(\Gamma_{L\sigma} + \Gamma_{R\sigma}) N_{1,2} + \sum_{\alpha} \Gamma_{\alpha\sigma} N_{2,1} [f_{\alpha\sigma}(E_{\sigma} + F(t)) + f_{\alpha\sigma}(E_{\sigma} + U + F(t))] = \sum_{\alpha} \Gamma_{\alpha\sigma} f_{\alpha\sigma}(E_{\sigma} + F(t)), \quad (2)$$

where $\Gamma_{\alpha\sigma} = 2\pi \sum_k |T_{k\alpha\sigma}|^2 \delta(\omega - E_{k\alpha\sigma})$ are the coupling constants and $f_{\alpha\sigma}$ are the Fermi functions.

Following the same approach, we obtain the expressions for the currents through the σ -level, as

$$I_{\sigma} = \frac{\Gamma_{\sigma}}{2} [(1 - N_{\bar{\sigma}})(f_R(E_{\sigma} + F(t)) - f_L(E_{\sigma} + F(t))) + N_{\bar{\sigma}}(f_R(E_{\sigma} + U + F(t)) - f_L(E_{\sigma} + U + F(t)))]. \quad (3)$$

The physical meaning of this expression is transparent: if the level $\bar{\sigma}$ is empty, transport via σ -level occurs at the slowly varying energy $E_{\sigma} + F(t)$. If the level $\bar{\sigma}$ is populated, it takes place at the energy $E_{\sigma} + U + F(t)$. In both cases, the current is proportional to the difference of the Fermi functions of the leads taken at the corresponding energy.

The current averaged over the period of the SAW oscillations, which is measured in the experiment,

$$I_{\sigma} = \frac{\Omega_0}{2\pi} \int_0^{2\pi/\Omega_0} dt I_{\sigma}(t), \quad (4)$$

is shown in Fig. 3 for the following set of parameters: $U = 0.6$ meV, $\Gamma_{\alpha\sigma} = 0.01$ meV, and the source-drain bias $V_{SD} = 0.001$ meV.

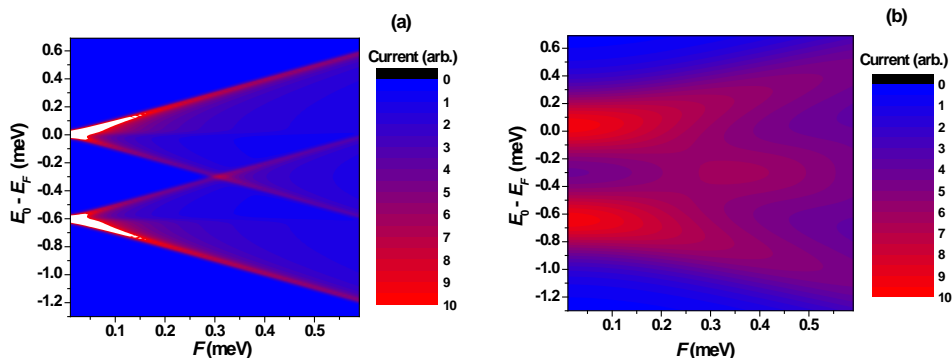


Figure 3. Calculated current through the structure at 100mK (a) and 1.5K (b).

One can see that the Coulomb blockade peaks associated with the two electron levels in the dot become split with the SAW power increased and form a peak in the middle when the lower branch of the upper peak merges with the upper branch of the lower peak resembling the experimental data. This property can be understood from the following point of view. Formally, we have a term $F(t)a_{\sigma}^{\dagger}a_{\sigma}$ in the Hamiltonian, which looks similar to the conventional term describing Rabi oscillations, except it creates and annihilates electrons at the same level. However, the level is broadened by coupling to the leads with $\Gamma \gg \Omega_0$, so both levels resonant to the SAW are inside this Γ window. Physically, the electron lifetime in the dot, $1/\Gamma$, is smaller than the period of the SAW oscillations and one electron with the energy $E + \Omega_0$ can emit phonon and escape to the right lead and the second electron with the energy E can come from the left lead and absorb this phonon. Accordingly, we can assume *dynamical* Rabi oscillations in the dot with the phonon-assisted tunnelling. This process is the dominating contribution to the averaged current. As a result of the Rabi shift, we have the levels splitting as $E \pm F$ and $E + U \pm F$. At $F = U/2$, two of the levels merge, as can be seen in Fig. 2. It should be emphasized that transport not only probes the level structure, but facilitates the level broadening which is extremely important for this observation of the phonon-assisted tunnelling in the adiabatic regime. It should be noted that the peaks are clearly seen at very low temperature only, being quite broadened already at 1.5 K. It explains the Coulomb blockade lifting at high SAW power seen in the experiment.

4. Summary

In summary, we studied electron transport through a quantum dot formed in the suspended nanobridge, which is mechanically excited via surface acoustic waves. We observe a shift of the Coulomb blockade peaks with increasing SAW power. This can be explained within the framework of “dynamical” Rabi oscillations.

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