Surface Acoustic Wave induced Transport in a Double Quantum Dot

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We report on non-adiabatic transport through a double quantum dot under irradiation of surface acoustic waves generated on-chip. At low excitation powers, absorption and emission of single and multiple phonons is observed. At higher power, sequential phonon assisted tunneling processes excite the double dot in a highly non-equilibrium state. The present system is attractive for studying electron-phonon interaction with piezoelectric coupling.

Electron-phonon coupling often leads to dissipation and decoherence problems in nanoelectronic devices. The decoherence in a tunable two-level quantum system (qubit), such as a double quantum dot (DQD) [1], is of particular interest in the recent light of quantum computation and information [2]. It was found that piezoelectric coupling to acoustic phonons is the dominant mechanism for inelastic transition between two charge states in a DQD [3], as confirmed by theory [4]. In analogy to quantum states in natural atoms – which dominantly couple to, and are successfully controlled by photons – the electronic states in solid state systems may be controlled by phonons, taking advantage of the strong electron-phonon coupling.

Due to the piezoelectric coupling in GaAs, surface acoustic waves (SAWs) can be generated by applying a microwave signal to an interdigital transducer (IDT) [5]. The accompanying propagating and oscillating potential has been used in several experiments to transport photo-generated electrons and holes in so-called ‘dynamical quantum dots’ [6]. In those experiments, however, the SAWs give rise to an adiabatic change of the electronic states, where the carriers remain in an eigenstate of the temporal potential.

In this Letter, we present non-adiabatic transitions in a lithographically defined DQD under irradiation of coherent SAWs. We observe resonant phonon assisted tunneling, where transport is well described by considering absorption and emission of one or multiple phonons during the tunneling process [7]. The present results unambiguously indicate a finite contribution of SAWs to the bosonic environment of a quantum two-level system formed by a DQD. Moreover, these transport measurements allow us to determine extremely small amplitudes of the local piezoelectric potential.

Figure 1(a) is a picture of our device showing the Ti/Au gate patterns of the interdigital transducer used for generating SAWs on the left, and the DQD on the right top on of a GaAs/AlGaAs heterostructure with a 2D electron gas (2DEG) 100 nm below the surface. The periodicity of the IDT is 1.4 μm, setting the SAW wavelength λSAW, and corresponding to a SAW frequency of about 2 GHz in GaAs [see lower left SEM micrograph in
The IDT design is characterized at room temperature using a different GaAs/AlGaAs heterostructure with two identical IDTs facing each other, allowing for a two-channel microwave measurement. The transmission and reflection spectra in Fig. 1(b) show a clear resonance at 1.92 GHz, as expected from the IDT design. The reflection dip is more than 3 dB, indicating that more than half of the incident power is absorbed in the IDT. The transmission reaches a maximum of -30 dB at resonance, implying additional loss in the device. Possible mechanisms for power loss are impedance mismatch, electromechanical conversion loss and Bragg reflection within the IDT. We found that the reflection and transmission spectra do not change when a DQD device is fabricated in the middle between the IDTs. By assuming identical characteristics for both IDTs, acoustic power at the site of the DQD is 15 dB less than the incident microwave power, P.

The DQD is formed in an etched channel of 600 nm width [see hatched dry etching regions in the lower right SEM micrograph in Fig. 1(a)] with appropriate voltages to the indicated gate electrodes, which have a 220 nm spacing [1].

All measurements described below, are performed in a dilution refrigerator with a base temperature of 50 mK. We have obtained similar results in two different samples, measured in different cryostats. The data shown here, are taken from one sample. Each dot contains ~10 electrons, has a charging energy of ~2 meV and a discrete energy level spacing of ~150 µeV. The inter-dot electrostatic coupling is ~200 µeV, and the tunneling coupling is weak (≪ 10 µeV) so that delocalization of states can be neglected. This weak coupling regime is suitable for studying electron-phonon interaction [3].

Figure 1(c) shows the single-electron tunneling current through the DQD versus gate voltages V_{gl} and V_{gr} with a large bias voltage of 500 µV with no microwave power (P = 0) applied to the IDT. The lower and upper (partly overlapping) triangular conduction regions correspond to electron-like and hole-like transport through the DQD, respectively [1]. Resonant tunneling through the ground states (GSs) of the two dots corresponds to the current peak at the base of the triangles (labeled GG), while other resonant tunneling between the left GS and the first and second excited states of the right dot are also observed (labeled GE1 and GE2). In the following measurements we simultaneously sweep V_{gl} and V_{gr} along the red arrow in Fig. 1(c), so that the energy difference $\Delta E = E_1 - E_2$ between the GS energies of the left dot ($E_1$) and the right dot ($E_2$) is varied. We observe a symmetric current profile around $\Delta E = 0$ representing elastic current through the DQD, while inelastic current at $\Delta E > 0$ associated with spontaneous emission of phonons is very small in the present experiment.

When microwaves are applied to the IDT, we observe significant broadening and splitting of the resonant tunneling peaks only at the IDT resonant frequency, $f_{SAW} = 1.9446$ GHz, as seen in the frequency dependence of the current spectrum in Fig. 2(a). The resonance frequency corresponds very well to that of the GaAs reference sample (1.92 GHz) of Fig. 1(b), where the slight deviation is ascribed to the different heterostructure and the lower temperature in the actual device. This good correspondence rules out photon assisted tunneling [8]. There is no reason why there should be an electromagnetic resonance coinciding with the IDT resonance frequency. We also exclude resonant heating, since the energy levels are well separated from the Fermi levels of the leads. The harmonic oscillation of the energy levels as described below, cannot be explained in terms of heating either. Note that no broadening is observed at off-resonant frequencies, also indicating that heating and spurrous electromagnetic coupling are negligible.

We now look in more detail at the mechanism of the SAW-induced current in Fig. 2(a). The traveling SAW causes a time-dependent potential $V_{ac} \cos(2\pi f_{SAW} t)$ between the two quantum dots, due to the piezoelectric and deformation coupling. For GaAs at this frequency, the piezoelectric effect is dominant and the deformation coupling can be neglected [9]. As the lithographical dot-dot distance is $d = 220$ nm and the SAW wavelength is $\lambda_{SAW} = 1.4 \, \mu$m, $V_{ac}$ is a fraction of the amplitude.
of the piezoelectric potential \( V_{pe} \), \( V_{ac} = \eta V_{pe} \), where \( \eta = \text{sin}(\pi d/\lambda_{SAW}) \approx 0.47 \). The time-dependent level spacing \( \Delta\tilde{E}(t) \) is therefore \( \Delta E + \eta V_{pe} \cos(2\pi f_{SAW} t) \). The peak splitting at resonance frequency and microwave power dependence of the current spectra is presented in Fig. 3(a). The peak splitting clearly increases with microwave power \( P \). In Fig. 3(d) the splitting is plotted (black dots) as function of the amplitude of the microwave voltage applied to the IDT, \( V_{IDT} \), confirming the linear dependence [10].

Since the tunneling rate (about 1 MHz for 100 fA current in our weakly-coupled DQD) is much smaller than \( f_{SAW} \), an electronic state in one dot acquires a phase, which is given by the integration of the oscillating potential, relative to another state in the other dot [11]. This non-adiabatic effect appears for example as photon assisted tunneling, as evidenced in various devices under microwave or far-infrared irradiation [8]. In our case, the oscillating potential is obviously induced by phonons. One can say that the DQD is exposed to surface acoustic phonons with energy \( h f_{SAW} = 8\ \mu eV \). The energy-dependent tunnel rate \( \Gamma(E) \) from the left dot to the right dot in the presence of the phonon field is given by the same theory [1,11]

\[
\tilde{\Gamma}(\Delta E) = \sum_{n=-\infty}^{\infty} J_n^2(\alpha)\Gamma(E + nhf_{SAW}),
\]

where \( n = 0, \pm 1, \pm 2, \ldots \) is the number of phonons involved in the emission (positive \( n \)) and absorption (negative \( n \)), \( \Gamma(E) \) is the tunnel rate without phonons and \( J_n^2(\alpha) \) is the squared \( n \)-th order Bessel function of the first kind evaluated at normalized amplitude \( \alpha = eV_{ac}/hf_{SAW} \) [see inset to Fig. 3(c)]. The modulated DQD current \( \tilde{I} \) then becomes [7]

\[
\tilde{I} = e|t|_{12}^2|\Gamma_R\sum_{n=-\infty}^{\infty} J_n^2(\alpha)\tilde{\Gamma}_R/4 + (n2\pi f_{SAW} - \Delta E/h^2)|^2,
\]

where \( |t|_{12} \) is the modulus of the tunnel coupling between the two dots, and \( \tilde{\Gamma}_R \) the tunnel rate from the right dot to the right lead. Inelastic current is allowed whenever the level spacing equals an integer number times the phonon energy, i.e. \( \Delta E = nhf_{SAW} \). The current thus consists of a number of satellite peaks, separated by the phonon energy \( h f_{SAW} \). The Bessel function describes the probability that an electron absorbs \( (n > 0) \) or emits \( (n < 0) \) \( n \) phonons. It should be noted that Eq. (2) approaches the adiabatic limit for \( \alpha \gg 1 \).

Our DQD device has a resonant current line width of 14 \( \mu eV \), even at zero microwave power, which is not sufficient to resolve phonon sideband with spacing \( h f_{SAW} \).
peaks are resolved, which may be useful in analyzing the energy spectrum of our DQD.

Finally, we comment on the measurement sensitivity to the piezoelectric potential in our experiment. As discussed above, the current spectra reflect the amplitude of the local piezoelectric potential. The lowest power at which we can resolve peak splitting is -58 dBm, corresponding to $V_{pe} = 24 \mu V$, which is several orders of magnitude smaller than the power used to induce dynamical quantum dots [6] and to induce lattice displacements measurable by optical interferometry [13]. The minimum detection power can be improved further by adjusting the DQD parameters. When the elastic current peak width is made smaller than the phonon energy, the piezoelectric potential can be derived from the amplitude of the phonon assisted tunneling current via the Bessel function dependence even for $\alpha \ll 1$. This may enable the measurement of lattice distortion due to vacuum fluctuations.

In conclusion, we have observed inelastic tunneling in a DQD two-level system coupled to a monochromatic SAW source. The transport through the DQD is well described by non-adiabatic Tien-Gordon theory for resonant tunneling between two discrete states with a time-dependent potential. We find that the DQD can be employed as a very sensitive SAW detector and is promising for studying electron-phonon interaction.

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