Interaction of a 2-level system with 2D phonons

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Abstract.
We report on the non-adiabatic interaction between 2D acoustic phonons and an artificial 2-level system in a GaAs/AlGaAs heterostructure. The 2-level system is formed by two discrete energy levels inside a double quantum dot, and monochromatic surface acoustic waves (∼2 GHz) are generated by an on-chip interdigital transducer (IDT). An IDT for better performance is proposed.

Keywords: 2-level system, quantum dots, surface acoustic waves
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INTRODUCTION

A double quantum dot (DQD) [1] forms a tunable device for studying the coupling of a two-level quantum system to a dissipative environment. The dephasing of such systems [2] is of particular interest in the light of quantum computation and information, where two-level quantum systems are the basic building blocks. Inelastic transitions between discrete energy levels, in which energy is exchanged with the environment in the form of bosons, are often undesirable. In Ref. [3] the inelastic transition rates in a DQD were described in term of the Einstein coefficients, relating absorption and stimulated emission to spontaneous emission. It was found that piezoelectric coupling to acoustic phonons is the dominant mechanism for relaxation, as confirmed by theory [4]. The experimental results of Ref. [3], nor the the theory of Ref. [4], however, are decisive about the nature (2D or 3D) of the acoustic phonons.

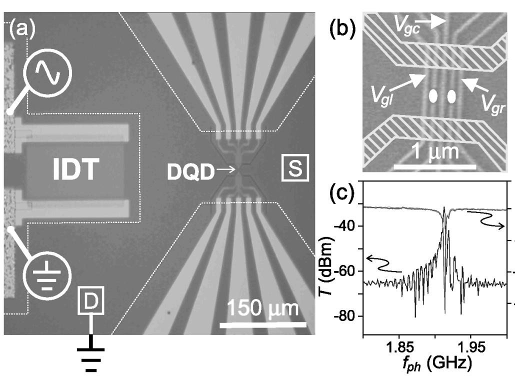

FIGURE 1. (a) Picture of the device. The IDT, DQD, source (S) and drain (D) are indicated. The IDT has a 1.4 μm periodicity. (b) Scanning electron micrograph of the DQD. The distance between the dots is 220 nm. (c) Transmission (T) and reflection (R) of a similar IDT at room temperature.

Here, we present experimental results on phonon induced electron transport through a lithographically defined DQD with an on-chip generator of monochromatic (1.94 GHz) surface acoustic waves (SAWs). The DQD acts as a sensitive detector for the tunable phonon environment, giving a direct measure for the amplitude of the local piezoelectric potential oscillations.

EXPERIMENTS

Our device is shown in Fig. 1(a), where the interdigital transducer (IDT) for generating the SAWs and the DQD are indicated [5]. Figure 1(b) is a scanning electron micrograph of the DQD, showing the Ti/Au gate pattern and the shallow etch region (hashed). 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(c) 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

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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.

Figure 2(a) 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 (T = 50 mK). The triangular conduction regions correspond to electron-like and hole-like transport through the DQD [1]. Resonant tunneling through the ground states (GG), as well as through the left dot ground state and the first and second excited states of the right dot are indicated (GE1 and GE2) We now simultaneously sweep V_{gl} and V_{gr} along the white arrow, so that the energy difference $\Delta E = E_1 - E_2$ between the ground state energies of the left dot (E_1) and the right dot (E_2) is varied.

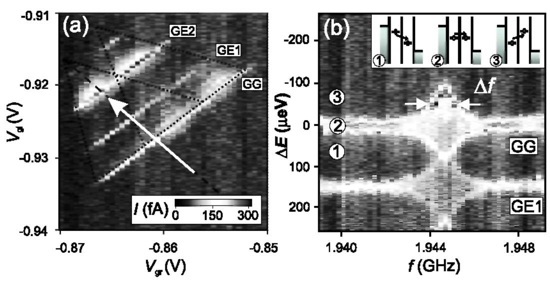

FIGURE 2. (a) Grayscale plot of the DQD current vs. gate voltages V_{gl} and V_{gr} at source drain voltage V_{SD} = 500 μV without SAWs. Resonant tunnelings lines are visible within the triangles. (b) Grayscale plot of the DQD current vs. ground state level spacing ΔE and microwave frequency f (P = -40 dBm). The schematics in the inset illustrate emission (1), elastic transport (2), and absorption (3).

Figure 2(b) shows the GG resonance when microwaves are applied to the IDT. Significant broadening and splitting of the resonant tunneling peaks only at the IDT resonant frequency, $f_{\mathrm{SAW}} = 1.9446$ GHz. Photon assisted tunneling [6] is ruled out, since 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. Note that no broadening is observed at off-resonant frequencies, also indicating that heating and spurious electromagnetic coupling are negligible.

The traveling SAW causes a time-dependent potential $V_{\mathrm{ac}}\cos(2\pi f_{\mathrm{SAW}}t)$ between the two quantum dots, due to the piezoelectric coupling. We have found [5] that our data reveal clear quantum behavior, and that transport can be described in terms of the nonadiabatic theory of resonant tunneling via two discrete states with a time-dependent energy difference [7]. One can say that the DQD is exposed to surface acoustic phonons with energy hf_{SAW} = 8 μeV. As the FWHM of the elastic current resonance is 14 μeV in our experiment, we have not succeeded in measuring clearly resolved satellites as in former DQD experiments [1]. IDTs with a higher resonance frequency, such as the 6 GHz IDT (hf = 25 μeV) in Fig. 3(a) would allow us to do so. The depicted IDT is double-fingered, i.e. it has 4 fingers per period instead of 2. In single-fingered IDTs, constructive interference occurs between propagating SAWs and reflected SAWs, thereby reducing the output of the IDT. In the double-finger geometry this problem is reduced by turning the internal interference into a negative one (see Fig. 3(b)).

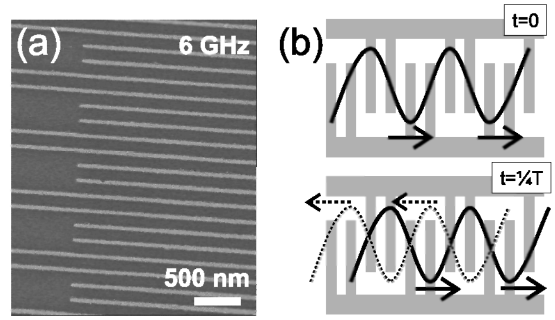

FIGURE 3. (a) Scanning electron micrograph of a double-fingered 6GHz IDT. (b) Schematics illustrating the destructive interference between right-moving SAWs and reflected (left-moving) SAWs in a double-fingered IDT.

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