Decoherence of electric dipole rotation in a double quantum dot

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Semiconductor double quantum dots (QDs) can be considered as a quantum two-level system (qubit) with high controllability [1] and is a promising candidate to implement a scalable quantum computer. In a similar way as Nakamura et al did for a superconducting single-Cooper-pair box [2], we introduced a short voltage pulse to the drain electrode and observed the coherent oscillation of the electric dipole. In this letter, we would like to discuss decoherence of our qubit.

We studied a lateral double QD fabricated in an AlGaAs / GaAs heterostructure (the inset of Fig. a). Before the pulse, a large source-drain voltage is applied and the localized states belonging to each QD are out of resonance. The inelastic current associated with phonon emission flows through the double QD. The left and right tunneling rates (Γ_L and Γ_R) are adjusted to be much larger than the phonon emission rate so that, for most of the time, an electron is practically localized in the left QD. At a time (t = 0), the source drain voltage becomes zero and the two localized energy levels get closer. Here we define ε as the energy difference between the localized energy levels. The electron trapped in the left QD starts oscillating between the two QDs. At a certain time ($t = t_p$) later, the source-drain voltage goes back to the large value. If the electron exists in the right QD at that moment, it can tunnel out to the right electrode and contribute to the pulse-modulated current. If the electron is in the left QD, the electric state after the pulse is the same as the state before the pulse and, therefore, does not give any current. We repeat this pulse sequence with repetition frequency f_{rep} = 100 MHz and pulse length t_p = 0.08 – 2 ns. We measured the current difference I_{mod} with or without the voltage pulse as a function of pulse length t_p. Clear oscillation of I_{mod} (oscillation frequency $\Omega/2\pi$ = 2.3 GHz and phase relaxation rate T_2 = 0.9 ns) can be seen in Fig. a. The circles are the experimental data and the line is the fitting curve of a damping cosine function. We also observed that it was possible to change the oscillation frequency which is related to the strength of inter-dot coupling Δ = 10 μeV, by changing the gate voltage between QDs.

In general, a coherent two-level system is coupled with several kinds of environments and loses its coherency. Total decoherence rate T_2^{-1} is a sum of the decoherence rates for each factor. Fig. b-d show the ε, Δ, and temperature dependence of the T_2^{-1} estimated from the current spectra for two samples; Sample I (black circle) and Sample II (white circle). As shown in Fig. b, the T_2^{-1} has a minimum at ε = 0, which is a common feature for any Δ. To analyze this, we presume there is a finite fluctuation in ε. This fluctuation $\delta\varepsilon$ is attributed to the background charge fluctuation in the electric circuit [3] and the fluctuation in the gate voltages. According to the relationship $\hbar\Omega = \sqrt{\varepsilon^2 + \Delta^2}$, the fluctuation $\delta\varepsilon$ leads to the fluctuation in Ω which brings on decoherence: decoherence rate $\Gamma_\varepsilon = |\delta\Omega|$. The dash-dotted line in Fig. b is the Γ_ε ($\delta\varepsilon$ = 1.6 μeV) which reproduces the ε dependence of the experimental T_2^{-1}. We obtained the similar results for the other Δ. The T_2^{-1} is minimal at ε = 0 because the first order derivative of Ω in terms of ε is zero. The finite T_2^{-1} at ε = 0 should be mainly attributed to the other sources of decoherence such as the electron-phonon interaction [4] and cotunneling. We calculated the decoherence rate Γ_{ph} caused by the electron-phonon interaction (dotted line in Fig. c and d) with a spin-boson model for an Ohmic spectral density [4] (we used dimensionless coupling strength of the electron-phonon interaction g ~ 0.03). We also calculated the cotunneling rates Γ_{cot} (solid line in Fig. c and d) with higher order Golden rule (we assume the left and right tunneling barriers are identical). Both Γ_{ph} and Γ_{cot} are comparable to the observed T_2^{-1}.

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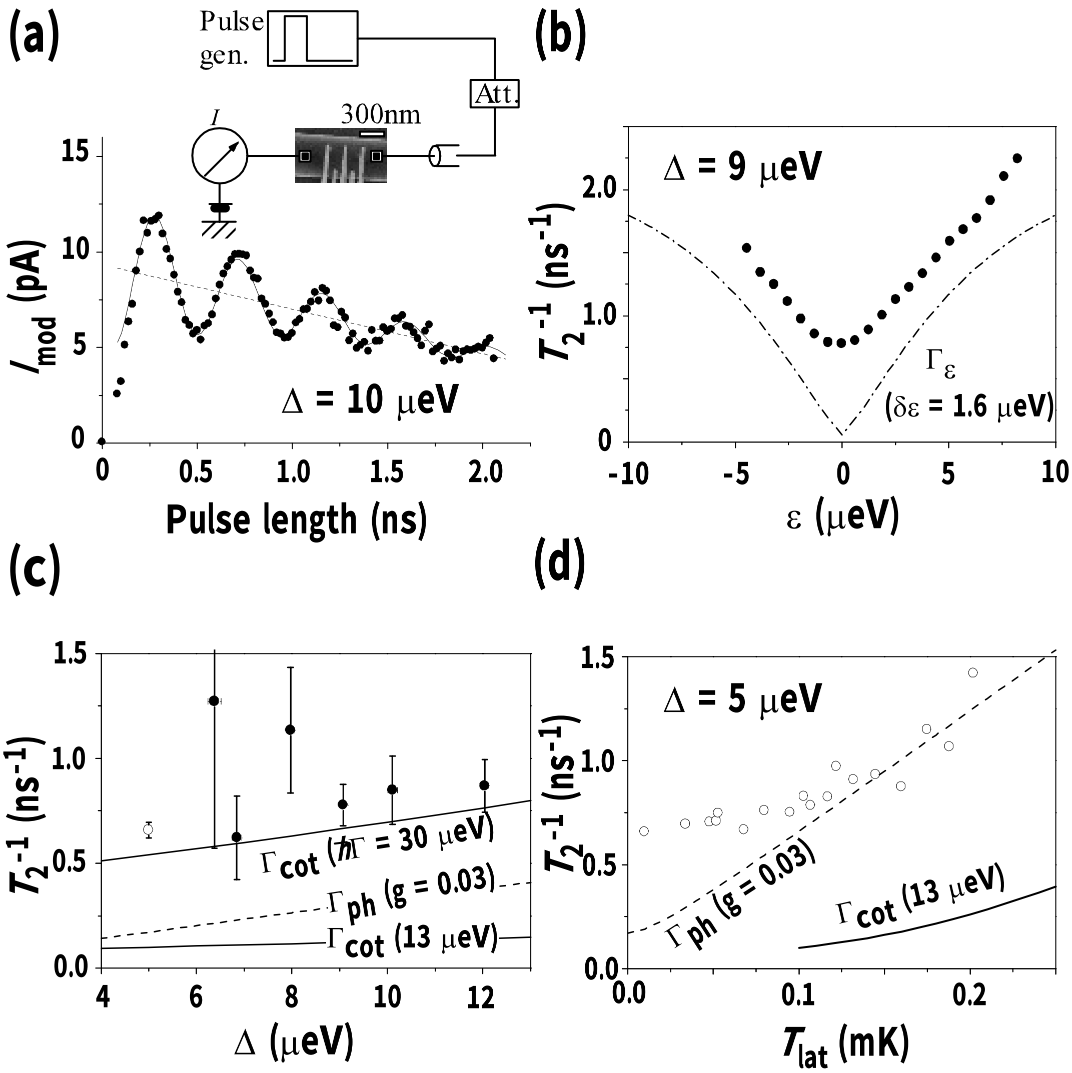

Fig. a Pulse-modulated current spectrum as a function of pulse length t_p. The solid line is the fitting curve of a damping cosine function. The dotted line represents the reduction of the inelastic current. The inset is a scanning microscope image of the sample and the schematic measurement setup.

Fig. b Energy difference ε dependence of the decoherence rate T_2^{-1} for Δ = 9 μeV. The dash-dotted line is a calculated T_2^{-1} due to a finite fluctuation in ε.

Fig. c Inter-dot coupling strength Δ dependence of the decoherence rates T_2^{-1} at ε = 0 for for sample I (black circle) and for sample II (white circle). The dotted line is the calculated T_2^{-1} caused by the electron-phonon interaction. The solid lines are the calculated cotunneling rates. The left and right tunneling rates are assumed to be $\hbar\Gamma_{L/R}$ = 30 μeV (for sample I) and 13 μeV (for sample II).

Fig. d Lattice temperature T_{lat} dependence of decoherence rate T_2^{-1} at ε = 0 for Δ = 5 μeV.