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Dissipative Landau-Zener transition in capacitance measurement on a double quantum dot

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We propose and demonstrate capacitance measurement for estimating the tunneling rate between two quantum dots. Under sinusoidal potential modulation on the double quantum dot, the charge dynamics is quantified with the capacitance defined by the induced charge due to the potential modulation. We show that the dynamics can be understood in terms of dissipative Landau-Zener transition, from which we can deduce the tunneling rate. To validate this measurement, density-matrix simulations are performed in the presence of phonon scattering with typical GaAs parameters, and we confirm that the dissipation plays a minor role. In practice, we employ wide-band capacitance measurement on a GaAs DQD and discuss the consistency with the simulation.

1. Introduction

A quantum two-level system such as a charge qubit in a semiconductor double quantum dot (DQD) is a fundamental building block for developing quantum circuits and for studying quantum dynamics [1]. The energy difference ε between the two localized states in a DQD and the tunneling coupling t_c between them can be tuned by external voltages, which is attractive for the purposes. In contrast to ε that can be determined precisely from various techniques [2], determination of t_c is often ambiguous. While t_c has been determined from microwave photon-assisted-tunneling spectroscopy [2] and the frequency of coherent oscillations [3], these schemes cannot be applied to the cases with significant decoherence. Other schemes such as from the width of a resonant-tunneling current peak [4] and the curvature of a charge stability diagram [5] can also be influenced by dissipation and charge fluctuations in the system. The alternative way we focus on is the Landau-Zener (LZ) transition, in which the detuning $\varepsilon = v\ t$ is linearly swept at a speed v through the avoided crossing at $\varepsilon = 0$ and investigate whether the final state remains the original state or not. The critical speed $v_{LZ} = 2\pi t_c^2/\hbar$ is directly related to t_c [6]. Interestingly, the theory suggests that this v_{LZ} is unchanged even in the presence of dissipation associated with fluctuations of ε [7]. This unique characteristics can be utilized in estimating t_c.

In this paper, we focus on a capacitance measurement, in which approximate LZ transitions are repeated with a sinusoidal wave $\varepsilon(t)$ at frequency f and we investigate whether the electron goes back and forth between the two dots or remains in a dot. A charge detector with a sinusoidal wave is used to detect this motion with a value proportional to the capacitance. The advantage of this scheme is that no state preparation is required. Sinusoidal waves are experimentally easier to be delivered to a low-temperature device than a linear wave. We have confirmed from numerical simulations that the capacitance is less sensitive to the dissipation. Moreover, the capacitance measurement is demonstrated on a one-electron GaAs DQD. Our results indicate that the capacitance measurement is useful in estimating t_c in a DQD.

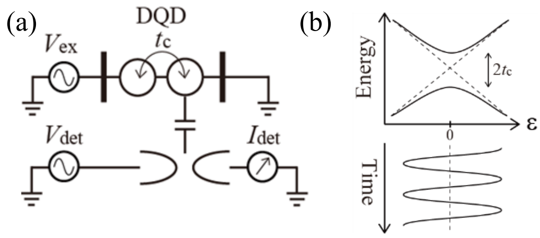

Fig. 1 (a) Schematic setup for the capacitance measurement. (b) Energy diagram and sinusoidal waves applied to the DQD.

2. LZ transition in capacitance measurement

Figure 1(a) shows a schematic setup for the capacitance measurement on an isolated DQD between two electrodes, where inter-dot tunneling t_c is present but no tunneling between the DQD and the electrodes is allowed. Application of sinusoidal voltage V_{ex} on the electrodes drives an electron in the DQD, and resulting charge dynamics is monitored by a nearby charge detector made of a quantum point contact (QPC). By applying another sinusoidal voltage V_{det} at the same frequency and the phase to the QPC as shown, resulting dc current I_{det} through the QPC is sensitive to the charge response on the right dot at the applied frequency f. This constitutes the capacitance measurement at various frequencies.

The charge dynamics in the DQD is illustrated in the energy diagram of Fig. 1(b). The electronic states exhibit an anti-crossing with a gap $2t_c$ at $\varepsilon = 0$. Application of V_{ex} induces sinusoidal energy offset $\varepsilon = \varepsilon_1 \cos\omega t$ ($\omega = 2\pi f$). When the amplitude ε_1 is sufficiently large ($\varepsilon_1 >> t_c$), dynamics around the anti-crossing at $\varepsilon \sim 0$ can be approximated to the LZ transition at $v = \varepsilon_1\omega$. However, we should test how well the dynamics can be approximated to the LZ transition. Particularly, the sinusoidal wave has long dwell time around the turning points ($\varepsilon \sim \pm\varepsilon_1$), where the relaxation may influence the estimate of t_c. We address this issue in numerical simulations.

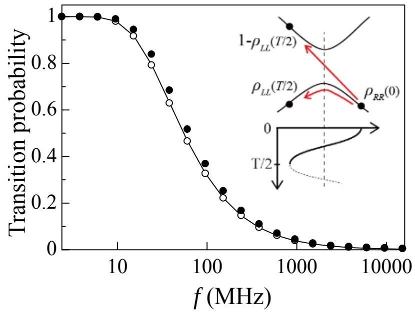

Fig. 2 Plot of LZ probability $\rho_{LL}(T/2)$ after a half cycle from the initial state $\rho_{RR}(0) = 1$. The open and solid circles represent the results in the absence ($\alpha = 0$) and the presence ($\alpha = 0.025$) of the dissipation with $t_c = 1.0$ μeV and $kT = 0$ μeV. The solid line corresponds to the exact solution for a linear drive. The inset indicates LZ transition during a half cycle of the excitation pulse.

3. Numerical simulations

We have employed the Lindblad master equation for a reduced density matrix $\rho(t)$ of the two-level system. The Hamiltonian includes $\varepsilon(t) = \varepsilon_1\cos\omega t$ and t_c, and Lindblad terms includes phonon scattering and dephasing processes. Standard piezoelectric electron-phonon interaction for a GaAs DQD is considered with a dimensionless coupling coefficient $\alpha = 0.025$, which explains phonon emission spectra in previous experiments [3]. Considering that our scheme is useful particularly when the coherency over the period is lost, we included a dephasing term that is sufficient to suppress the interference between the repeated LZ transitions.

This simulation is useful in understanding the dynamics for various cases including the sinusoidal drive. As this is a perturbative approach, however, we have confirmed the consistency with the exact solution available under limited conditions. Figure 2 shows a LZ probability $\rho_{LL}(T/2)$ after a half cycle from the initial state $\rho_{RR}(0) = 1$. The open and solid circles represent the results in the absence ($\alpha = 0$) and the presence ($\alpha = 0.025$) of the dissipation. They are slightly deviated from the exact solution for a linear drive (solid line even in the presence of the dissipation). Considering that the deviations remain minor, the dynamics can be approximated to the dissipative LZ transition.

For the periodic wave of interest, the steady state solution with $\rho(t) = \rho(t + T)$ is obtained from the one-period propagator that is obtained by numerically integrating the Lindblad master equation. The capacitance is calculated from the in-phase component of the fundamental mode in the Fourier transform of $\rho(t)$. The solid line in Fig. 3 shows the normalized capacitance C (set to unity in the low frequency limit) as a function of the frequency. A sharp transition from $C = 1$ to 0 is seen at $f \sim t_c^2/\varepsilon_1\hbar \sim 100$ MHz. Therefore one can estimate t_c by observing this critical frequency.

4. Capacitance measurement

The capacitance measurement is performed with a one-electron DQD formed in a GaAs/AlGaAs herterostructure at 24 mK and zero magnetic field. The capacitance is measured at $\varepsilon_1 = 40$ μeV. Since this is smaller than a few meV of the energy spacing and the addition energy of the dots, the system can be regarded as a two-level system. The normalized signal intensity proportional to the capacitance is measured in a wide frequency range as shown by solid circles in Fig. 3. The signal decreases with increasing f dramatically at around $f = 100$ MHz. This feature is fitted to the simulations (solid line) with a parameter $t_c = 1.6$ μeV. Apart from the small deviation at $f \sim 10$ MHz, the overall frequency dependence can be explained with the LZ transition in the capacitance measurement.

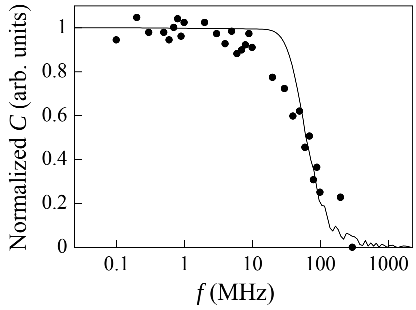

Fig. 3 Plot of signal intensity proportional to the capacitance as a function of frequency. The solid line represents the simulated curve with $t_c = 1.6$ μeV and $kT = 2$ μeV.

5. Conclusions

We have proposed and demonstrated capacitance measurement for estimating the tunneling coupling in a DQD. This scheme will be useful for various materials, such as Si and nanotubes, where a DQD and a charge detector are available.

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