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Coherent oscillations of charge states in a Si single-electron pump at 4.2 K

Gento Yamahata[1], Sungguen Ryu[2], H. -S. Sim[2],
Nathan Johnson[1], Masaya Kataoka[3], and Akira Fujiwara[1]

[1] NTT Basic Research Laboratories
NTT Corp., 3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa 243-0198, Japan.
Phone: +81-46-240-2478 E-mail: yamahata.gento@lab.ntt.co.jp
[2] Department of Physics, Korea Advanced Institute of Science and Technology
373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, Korea.
[3] National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW, United Kingdom.

Abstract

We observe anomalous oscillations of current generated by a Si single-electron (SE) pump as a function of gate voltage at 4.2 K. To explore the origin of the oscillations, we develop a theoretical model, in which coherent charge oscillations in a quantum dot (QD) are assumed. Non-adiabatic excitation of a charge state in the QD during the SE pumping leads to a quantum superposition state. The wave function of the state can coherently evolve between left and right in the QD. The motion can be detected by a resonant level in the exit barrier, resulting in current oscillations. Calculations by the theoretical model agree well with the experiments, suggesting that the current oscillations originate from the coherent time evolution.

1. Introduction

In the last 15 years, quantum coherent oscillations of electronic states have been demonstrated using semiconductor *double* QDs in several groups [1-3]. In contrast, such oscillations in a *single* QD is much more difficult to observe because the detection method of the oscillations with a speed of typically more than 100 GHz is difficult to implement. A dynamic QD in surface acoustic waves with a one-dimensional channel is a method for the detection [4], but the structure is complicated and the detection sensitivity is low. Here we report a new method to detect the coherent oscillations in a single QD using a Si tunable-barrier SE pump [5, 6] with a resonant level.

2. Device structure and operating principle

We fabricate a Si nanowire transistor with a double-layer gate structure (Fig. 1a) [5]. Application of a DC voltage to the upper gate (V_{UG}) induces electrons in the wire. The entrance and exit lower gates are used to create tunnel barriers in the wire by applying DC voltages (V_{ent}, V_{exit}), leading to formation of a gate-defined QD between the entrance and exit barriers. To pump electrons via the QD, we also apply a high-frequency sinusoidal signal with pumping frequency f_{in} to the entrance gate. As a result, an electron captured by the QD from the source is eventually ejected to the drain (Fig. 1b), leading to a current plateau with $I = nef_{in}$ (Fig. 1c), where n is an integer number and e is the elementary charge. The current is measured by a commercial ammeter and the measurement temperature is 4.2 K in liquid He.

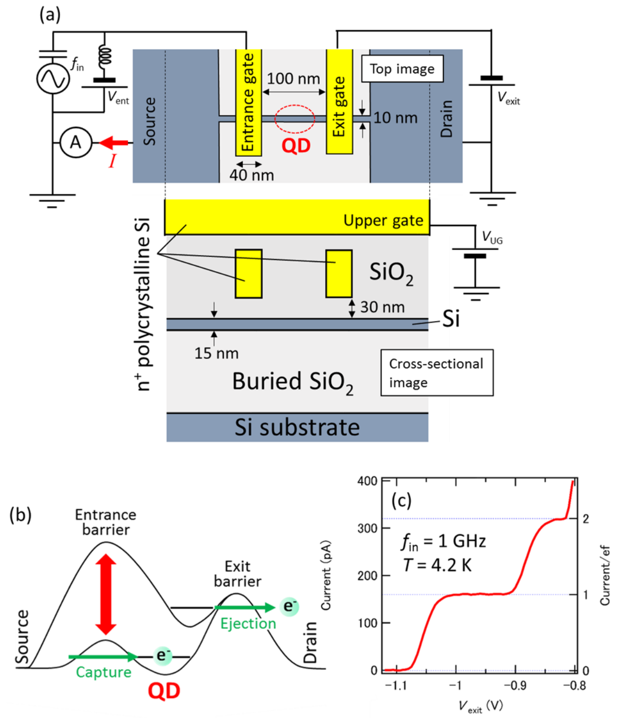

Figure 1 (a) Top and cross-sectional schematic images of the device with electrical connections. (b) Operating principle of SE pumping. (c) Typical current plateau of the SE pump as a function of V_{exit}, where $V_{ent} = -1.3$ V, $V_{UG} = 2.5$ V, $f_{in} = 1$ GHz, and $T = 4.2$ K.

3. Results and discussion

Figures 2a and 2b show dI/dV_{exit} maps as a function of V_{ent} and V_{exit} at $f_{in} = 1$ and 2 GHz, respectively. The pumping current level normally becomes zero in a region above the ejection line (dashed lines) of the exit barrier, where the QD energy level is lower than the barrier top and thereby the ejection rate becomes sufficiently low. However, we observe a current in the region, indicating the existence of an additional tunneling path, which is most likely a trap level in the exit barrier [7]. More importantly, the current anomalously oscillates on the map and the oscillation period is proportional to f_{in}. This fact indicates that the oscillations do not originate from Coulomb oscillations of an unintentionally-formed QD or the structure of phonon density of states.

To explore the origin of the oscillations, we develop a theoretical model, in which we assume coherent time evolution of

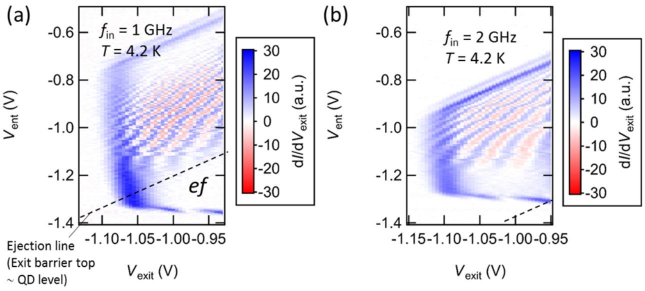

Figure 2 dI/dV_{exit} as a function of V_{ent} and V_{exit} at (a) f_{in} = 1 GHz and (b) 2 GHz, respectively, where V_{UG} = 2.5 V and the power of the high-frequency signal is 7 dBm.

the electronic states in the QD. When the rise of the QD level is faster, the population probability of the excited states by a single electron increases due to non-adiabatic excitation [8], which is confirmed by the fact that the current flow above the ejection line increases with increasing f_{in}. Then, the electronic ground and excited states can be coherently superposed. Note that only the first excited state is taken into account in this study for simplicity. In such a case, the wave function of the coherent superposition state can evolve as a function of time between the left ($|L\rangle$) and right ($|R\rangle$) sides in the QD (Fig. 3a) [4, 9]. When the energy of the superposition state is aligned with the trap level, the electron is ejected to the drain due to resonant tunneling. Since the tunneling occurs for a short time, the tunneling probability can depend on the location of the wave function. As a result, the current level can be low (high) when the wave function is $|L\rangle$ ($|R\rangle$). This model also explains the frequency dependence of the oscillation period in the dI/dV_{exit} maps. Figure 3b shows a schematic of the coherent oscillations and energy levels of the QD as a function of time. Since frequency f_{coh} of the coherent oscillations is determined by the energy spacing ΔE between the ground and excited states ($f_{coh} = \Delta E/h$, where h is the Planck constant) and it is independent of f_{in}, the energy difference of the $|R\rangle$ state after one period of the oscillations increases with increasing f_{in} ($\Delta_1 < \Delta_2$ in Fig. 3b). Since V_{ent} and V_{exit} changes the QD and trap levels, a larger voltage shift is necessary to detect the different current peaks by one period at higher f_{in}.

To be more quantitative, we formulate the model by defining two time points (t_0, t_1) as indicated in Fig. 3b. t_0 is an initial time of the oscillations and we simply assume that it is the time when the QD level is aligned with the Fermi level E_f. t_1 is the time when the QD level is aligned with the trap level. In this model, probability P_{coh}, with which the state is $|R\rangle$ at the time of the resonant tunneling, can be written as:

$$P_{coh} = [1 - \cos\{2\pi f_{coh}(t_1 - t_0)\}]/2. \quad (1)$$

Using the gate and QD capacitances, t_0 and t_1 can be written as a function of V_{ent} and V_{exit}. By carefully extracting the capacitances from the experimental data, P_{coh} is calculated only with input parameters of ΔE and E_f. Figures 4a and 4b show calculated P_{coh} at f_{in} = 1 and 2 GHz, respectively. The calculated oscillations agree well with the experimental data. A value of ΔE ~ 0.75 meV reproduces the experimental data, which corresponds to a confinement of about 45 nm. This value would be reasonable because the first electron in the QD is located at the bottom of the potential. These calculations suggest that the observed current oscillations originate from coherent time evolution of electronic states. We stress that the coherent oscillations with f_{coh} of about 180 GHz (ΔE = 0.75 meV) are difficult to observe in a conventional double-QD charge qubit because ΔE is much smaller in that case.

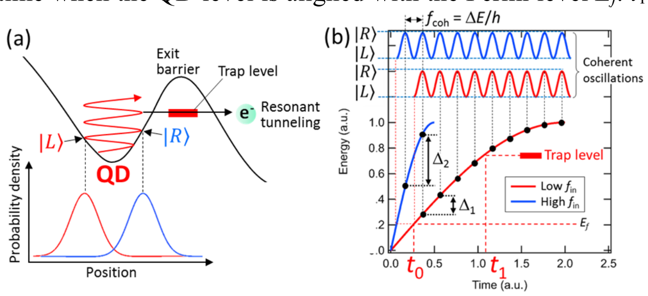

Figure 3 (a) Schematic of the coherent time evolution of the electronic states. (b) Energy of the QD as a function of time at low (red) and high (blue) f_{in} with the corresponding coherent oscillations between $|L\rangle$ and $|R\rangle$. Black dots corresponds to current peaks, which are observed when the trap level is aligned with them.

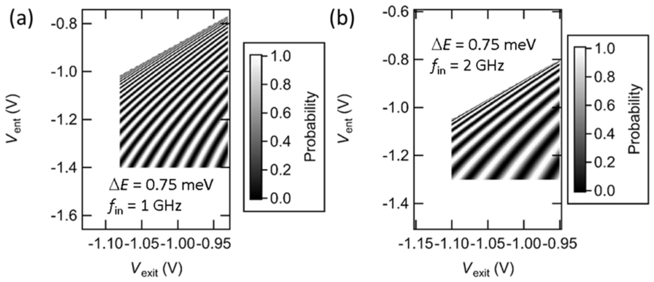

Figure 4 Calculated probability of the coherent oscillations at (a) f_{in} = 1 GHz and (b) 2 GHz, respectively, where V_{UG} = 2.5 V, the power of the high-frequency signal is 7 dBm, and $E_f = -50$ meV. To reproduce the experimental data, we set ΔE = 0.75 meV.

4. Conclusions

We have demonstrated the fast coherent time evolution of electronic states at about 180 GHz in a Si SE pump. Since the detection sensitivity is much better than the previous study, our results open a window into investigation of quantum physics of a single electron [9, 10]. In addition, the fast oscillations are possibly suitable for qubit operation, which would stimulate further studies of control of quantum charge states.

Acknowledgements

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