Single-electron energy dissipation processes mediated by slab mode phonons observed for suspended silicon double quantum dots

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1. Introduction

Co-integration of nanoelectromechanical systems (NEMS) and silicon nanodevices enables us to explore a number of new phenomena associated with strong coupling of a single electron and a low-dimensional nanomechanical mode, such as phonon blockade [1], single-electron quantum shuttle [2] and the quantum ground state of a mechanical resonator [3]. Manipulation of nanophononic states in scaled silicon nanostructures may be exploited to develop a novel approach to thermal management and energy transfer interaction in '*Beyond CMOS*' information processing. This paper presents observation of energy dissipation processes of a single-electron mediated by slab-mode phonon emission by using inelastic tunneling spectroscopy with electrostatically-controlled suspended silicon double quantum dots (SDQDs)

2. Inelastic tunneling spectroscopy with suspended double quantum dots

The SDQDs with two side gates (see Fig. 1) were fabricated on a 50-nm-thick heavily-P-doped silicon-on-insulator (SOI) substrate by using EB lithography and ECR-RIE. The SiO_2 layer under the film was etched out by hydrofluoric acid, and then the SDQDs were thermally oxidized to passivate the device surface and reduce the SDQDs dimensions [4]. Bias voltages applied to the two side gates, V_{g1} and V_{g2}, control the electro-chemical potentials of the individual DQDs. A single-electron tunnels through DQDs elastically when the chemical potentials align.

Figure 2 shows the drain current measured at 120 mK with V_{ds} = 200 μV as a function of V_{g1} and V_{g2}. We observed typical characteristics for a serial DQDs structure [5], e.g. two sets of charging lines at the crossing of which appears a pair of triangular regions where the current is enhanced (Fig. 3). Figures 4(a) and (b) plot the drain current with V_{ds} =500 μV and −500 μV when the two gate voltages were swept in order to change the energy difference ΔE between the DQDs (along to the white arrow in Fig. 3). A broad current peak across the bias triangle was deconvoluted well into eight current peaks. In Fig. 4(a), the largest peak centered at $\Delta E = 0$ corresponds to elastic tunneling, and the peaks centered at $\Delta E > 0$ correspond to inelastic tunneling of electrons with phonon emission. The small peaks centered at $\Delta E < 0$ are presumably caused by co-tunneling.

3. Analysis of single-electron energy dissipation via slab-mode phonon emission

The electron-phonon interaction was then analyzed for a 40-nm-thick Si slab sandwiched by 10-nm-thick SiO_2 layers with embedded cylindrical DQDs. Our theoretical model is based on that reported by Liao *et al.* [6] but extended by taking account of both geometrical asymmetry and finite height of the DQDs. Both dilatational and flexural phonon modes were studied. Figure 5 shows the phonon spectral density $J(\omega)$ calculated for the modeled SDQDs. By comparing the experimental results in Fig. 4 and the calculated spectral density, we found that a relatively large peak observed at ΔE = 260 μeV (shown by a red arrow in Figs. 4(a)) is attributed to a group of sharp peaks in the spectral density caused by enhanced electron-phonon interaction due to van Hove singularities of dilatational mode phonons. The other peaks observed at ΔE = 100 μeV, ΔE = 180 μeV and ΔE = 390 μeV also agree well with the calculated results. Since the present simple model does not include the effects of the electron temperature, the phonon dissipation or the tunneling rates of the barriers, we cannot discuss the current peak heights and widths. Nevertheless, a good agreement in the peak energies was obtained both for positive (Fig. 4(a)) and negative (Fig. 4 (b)) source-to-drain bias voltages. This fact clearly discards the possibility of the state quantization as a physical origin of the peaks. Figure 6 shows the peak energy in the spectral density associated with one of van Hove singularities of dilatational mode as a function of Si slab thickness. The peak energy increases approximately inverse proportional to the slab thickness. These results allow us to envisage the possibility of tailoring the electron-phonon interaction in SDQDs via the structural parameters and also observing fundamental processes of single-electron energy dissipation even at higher temperatures.

4. Conclusion

We have successfully demonstrated the inelastic single-electron tunneling mediated by slab phonon emission in the SDQDs. A good agreement between the experimental and theoretical phonon peak energies enables us to study not only the possibility of electron-phonon engineering but also fundamental energy dissipation processes of tunnelling electrons in in Si NEM structures.

References

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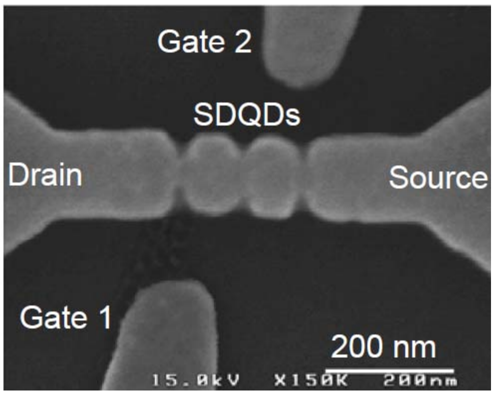

Fig. 1 The SEM image of fabricated SDQDs structure. The SDQDs are connected to the source and drain electrodes. The electro-chemical potential in the each dot was controlled with the each side gates.

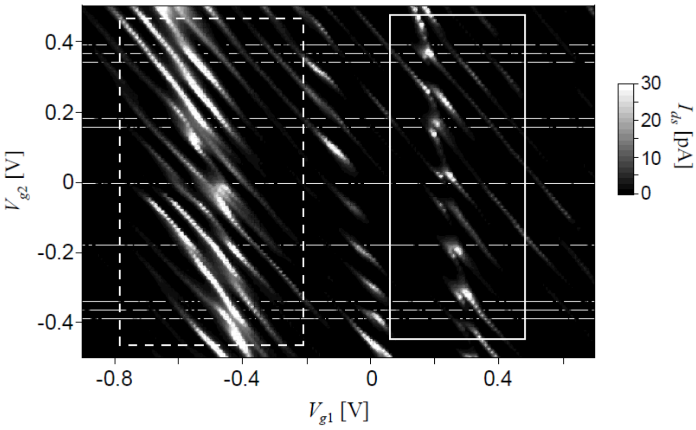

Fig. 2 The drain to source current measured at 120 mK with Vds = 200 μV as a function of Vg1 and Vg2. The typical characteristics of the single-electron tunnelling via the DQDs were observed in the region shown by the solid rectangular while the current peaks were more complicated in the region shown by a dashed rectangular due to the existence of unintentional QDs.

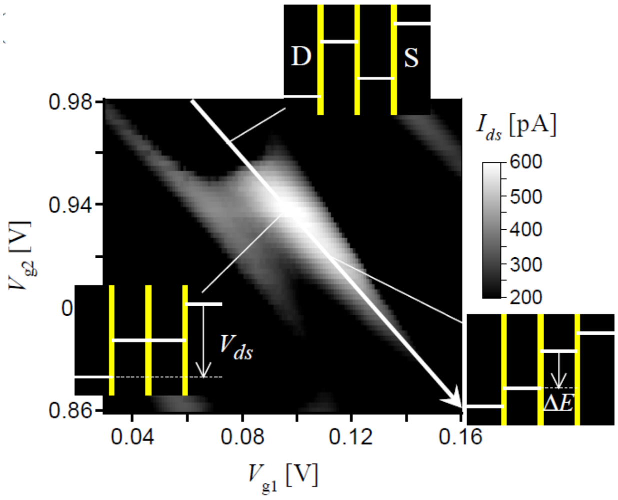

Fig. 3 A pair of overlapped bias triangles. The potential energy difference between the DQDs, ΔE, can be detuned by sweeping the gate voltages along a diagonal arrow. The insets schematically show the energy diagrams of the potential detuning at different gate voltages for a fixed V_{ds}.

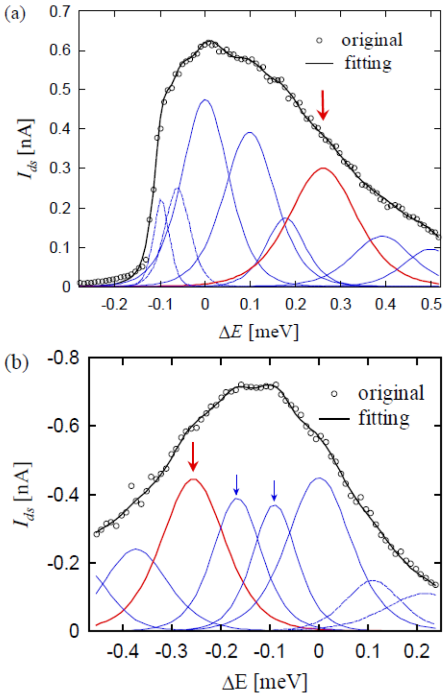

Fig. 4 Drain-to-source current I_{ds} versus the potential difference ΔE with (a) V_{ds}=500 μV and (b) V_{ds}=–500 μV. The original data (circle) are fitted by a sum of peaks.

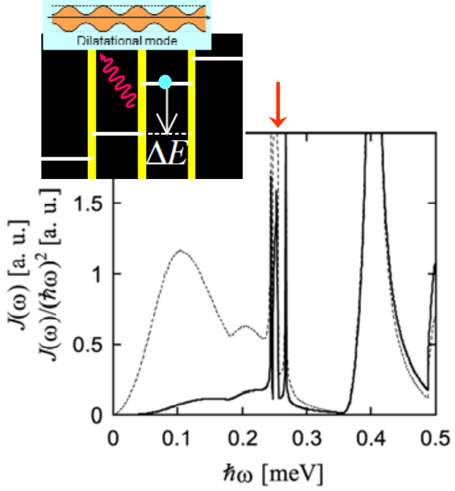

Fig. 5 The calculated phonon spectral density in the fabricated SDQDs (solid line). The dashed line represents the ratio of the phonon spectral density to the square of the phonon energy. The singularity indicated by the arrow corresponds to the zero group velocity of dilatational mode that is schematically shown in the inset.

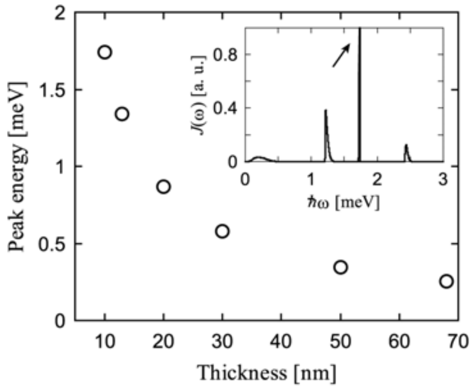

Fig. 6 The relation between phonon energy of the enhancement peak center and slab thickness. The inset shows phonon spectral density of 10-nm-thick Si slab.