Improved Accuracy of Single-Hole Pumping via Silicon Quantum Dot by Dynamic Gate Compensation

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A single-charge pump with a tunable-barrier dynamic quantum dot (QD) is promising for applications to quantum current standards [1] and quantum information devices [2, 3]. While there have been several reports on high-accuracy single-electron pumping with a sub-ppm level [1], the pumping accuracy still needs to be improved. Here, we report on the low-temperature measurements of a single-hole (SH) pump, which is expected to operate more accurately than a single-electron pump due to the heavy effective mass of holes [4]. In the device, we suppress the change in the QD energy by dynamic gate compensation to improve the pumping accuracy, leading to an expected error rate of less than 1 ppb.

The device has two fine gates on a silicon nanowire with an diameter of about 10 nm (Fig. 1a). Single holes are transferred one by one via the QD between the two gates by applying a DC voltage (V_{exit}) to the right exit gate and voltage pulses with a frequency of f to the left entrance gate, generating a DC current $I_{\mathrm{P}} = ef$, where e is the elementally charge. In this device, the QD potential rises with the rise of the entrance barrier because the entrance gate is capacitively coupled with the QD. Therefore, holes initially loaded in the QD escape to the source during the rise of the QD (Fig. 1b), and the ratio of the escape rates between the second and first holes (Γ_2/Γ_1) determines the capture accuracy. Since there is a difference in the time at which the first and second holes exceed the Fermi level E_{F}, Γ_1 becomes small during that time, making the effective Γ_2/Γ_1 larger. This indicates that the rise of the entrance barrier should be much faster than that of the QD potential for high-accuracy pumping. However, this rise ratio is determined by the device structure and is difficult to change by single-gate pulse operation.

To change the rise ratio, we applied dynamic gate compensation [5] to the SH pump. This is done by applying voltage pulses with an opposite polarity to the exit gate (blue arrows in Fig. 1b). This increases the difference in the rise speeds between the entrance barrier and QD, leading to smaller Γ_1 (better accuracy). Figure 1c shows $|(ef - I_{\mathrm{P}})/ef|$ without (red) and with (blue) dynamic gate compensation. We fit both sides of $|(ef - I_{\mathrm{P}})/ef|$. The cross-section points of the extended lines of the fit lines indicate the theoretical lower bound of the error rate. The accuracy improves from about 1 ppm to less than 1 ppb by gate compensation. This excellent level of accuracy could be important not only for metrological applications but also for quantum-device applications.

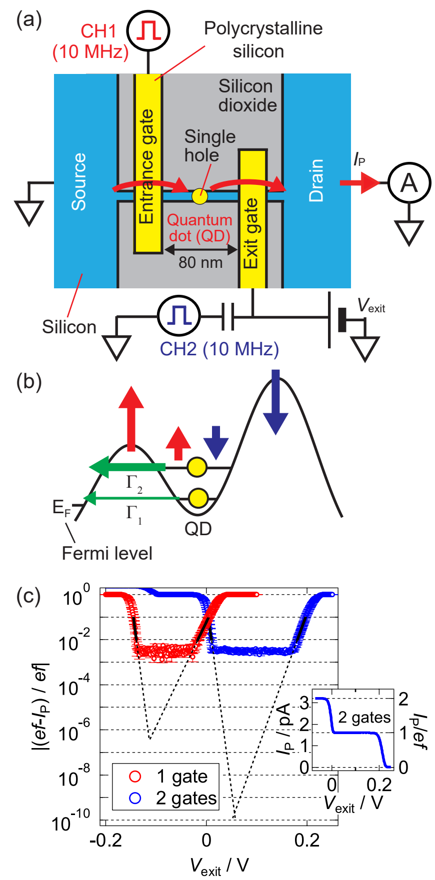

Fig. 1. (a) Schematic of the SH pump with some of electrical connections. P-type source and drain were formed by boron doping. Device was cooled in dilution refrigerator. (b) Schematic potential diagram during rise of entrance barrier with fall of exit barrier, which suppresses QD potential rise. (c) $|(ef - I_{\mathrm{P}})/ef|$ and I_{P}/ef (inset) as function of V_{exit} at 50 mK.

References

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