‘Cutoff Frequency’ of Quantum-Dot Single-Electron Pump

Ye-Hwan Ahn[1, 2], Changki Hong[3], Young-Seok Ghee[4], Yunchul Chung[3], Myung-Ho Bae[1] and Nam Kim[1]
[1]Korea Research Institute of Standards and Science, Daejeon 34113, Republic of Korea
namkim@kriss.re.kr
[2]Department of Physics, Korea University, Seoul 02841, Republic of Korea
[3]Department of Physics, Pusan National University, Busan 46241, Republic of Korea
[4]Department of Physics, Chonnam National University, Gwangju 61186, Republic of Korea

***Abstract*—We have investigated a ‘cut-off frequency’ f_c beyond which the quantized charge pumping phenomena disappear in a quantum-dot (QD) pump. We have observed a shift of f_c in the opposite direction to that of δ_2 parameter, the figure of merit for the current-plateau flatness, depending on the potential profiles of the QD which can be controlled by a plunger gate. In relation with f_c, we discuss the level-shift rate of a QD quasibound state in a nonadiabatic pumping phase.**

***Index Terms*—Charge pumps, current measurement, measurement standards, semiconductor devices, single electron devices, single electron transistors**

I. Introduction

Quantized electron pump based on a quantum dot (QD) is a promising candidate for the quantum current standard [1]-[3]. In order to obtain 10^{-8} level accuracy with a single electron pump [4], either precision measurement technique is to be improved or the output level of a pump must be increased at least with an order of magnitude. The simplest way to increase the output current level is to increase the operation frequency. However, it was turned out that increasing the microwave frequency resulted in non-adiabatic effects [5]. In this summary paper we report that there exists a cut-off frequency f_c beyond which single electron pumping does not work. We have investigated a potential dependence of f_c by varying the potential profile of the QD, which is controlled by a plunger gate.

II. EXPERIMENT AND DISCUSSION

Figure 1(a) shows a schematic diagram of our pump device [6]. The device is fabricated on the surface of a 2DEG wafer based on a GaAs/AlGaAs heterostructure. The pump device is composed of three pair of QPC (quantum point contact) gates, two of which are an entrance- and exit-gate QPC’s controlling respectively the entrance- and exit-potential barrier heights of the QD formed between these gates. The other one is a plunger gate QPC which is designed to tune the QD potential depth or the QD energy state. In this experiment, the three lower gate voltages are fixed for optimal tuning while the upper gates are used as entrance, plunger and exit gates separately. The width of each gate is 150, 75, and 75 nm, respectively for the entrance, plunger and exit gates, whose gaps are designed to be 75 nm. All the measurements are performed at 4.2 K without magnetic fields in liquid helium.

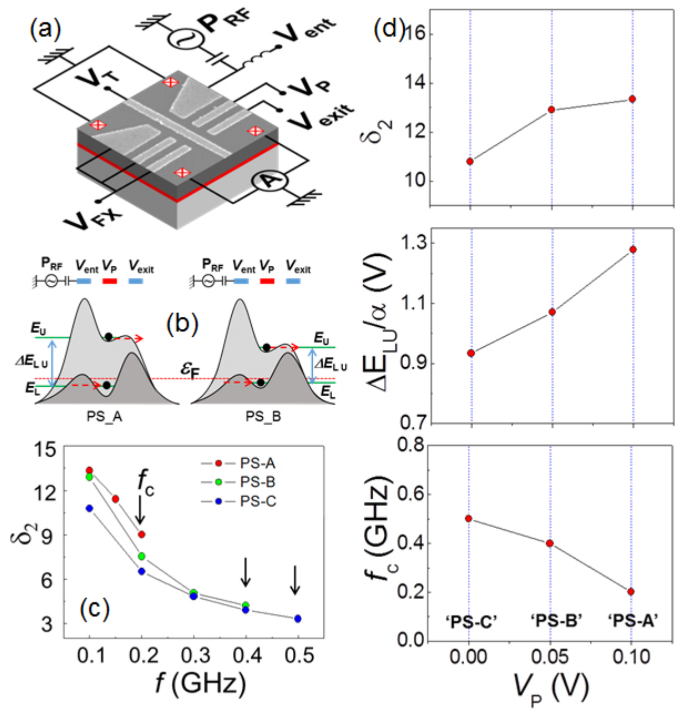

Fig. 1. (a) Scanning electron microscopic picture of our device and the measurement scheme. A QD forms on 2DEG underneath the gates. (b) Schematic diagram illustrating loading and unloading process. (c) δ_2 vs f for various $V_{\rm P}$, for instance $V_{\rm P}$ =0.0, 0.05, 0.1 V corresponding to ‘PS-C’,‘PS-B’ and ‘PS-A’. (d) Three physical parameters δ_2, $\Delta E_{\rm LU}/\alpha$ and f_c vs $V_{\rm P}$. δ_2 and $\Delta E_{\rm LU}/\alpha$ are obtained for f =100 MHz.

It is known that the flatness parameter δ_2 of the 1st current plateau decreases as the pumping frequency increases [1][6]. Here δ_2 is a fitting parameter obtained by fitting the decay cascade model to experimental data [7]. We investigate the frequency dependent δ_2 for various potential shapes of the QD. We varied the potential shapes using the plunger gate as illustrated in Fig.1(b). As the plunger gate voltage $V_{\rm P}$ increases the potential depth of the QD deepens the more, leading to increased δ_2 [6], which is confirmed in Fig. 1(c) and (d).

Figure 1(c) shows monotonic decrease of δ_2 as a function of frequency for three different potential shapes ‘PS-A’, ‘PS-B ’and ‘PS-C’ corresponding to $V_{\rm P}$ = 0.1 V, 0.05 V and 0.0 V respectively in decreasing $V_{\rm P}$ order. But we find that a ‘cutoff frequency’ f_c exists above which pumping phenomena disappear depending on each potential shape and f_c survives

978-1-4673-9134-4/16/$31.00 ©2016 IEEE

up to higher frequency for the shallower potential dip or 'PS-C' than for the deeper potential 'PS-A'.

The bottom panel of Fig. 1(d) summarizes the results of f_c for three different potential shapes, 'PS-A', 'PS-B 'and 'PS-C'. This decreasing tendency of f_c is contrasted with the increment of δ_2 with V_{P} [Fig. 1(d)]. The decreasing δ_2 with f can be understood qualitatively by considering that the loading and unloading probability could become much less than 1 as the modulation frequency becomes higher, which was described by the authors [1]. The authors [1] proposed a theoretical model and analyzed frequency dependency of the pumping accuracy. They predicted that nonadiabatic quantized-charge pumping model does not work at high frequency where adiabatic condition in the loading and unloading phase is not satisfied.

However, the authors [5] reported nonadiabatic excitations in localized quasibound states on QD. We presume that the nonadiabatic excitations could lead to influence the pumping accuracy, which was neglected in the model [1]. Focusing on the nonadiabatic effects on the quasibound state, we searched for relationships between the 'cutoff frequency' f_c and the level-shift rate of a quasibound state on a QD. In order to quantify the level-shift rate, we investigated a physical parameter called as 'tunneling blockade gap' denoted as ΔE_{UL} which is illustrated in Fig. 1(b) [8]. Figure 1(b) depicts the loading and unloading process as the entrance potential barrier varies. Here, E_{L} and E_{U} denote the energy level where loading and unloading process sets in and out respectively. Thus $\Delta E_{\mathrm{UL}} = E_{\mathrm{U}} - E_{\mathrm{L}}$ characterizes the tunneling blockade gap energy, because, if local bound state $\varepsilon(t)$ in the QD is located inside the gap ΔE_{UL} during the cycles of entrance-potential modulation, loading and unloading is prohibited by the definition of E_{L} and E_{U}. Pumping requires large amplitude V^{rf} of microwave to overcome the blockade gap energy. This is the condition for pumping; $E_{\mathrm{L}} > \varepsilon_{\mathrm{min}}$ and $E_{\mathrm{U}} < \varepsilon_{\mathrm{max}}$ where $\varepsilon_{\mathrm{max}} = \alpha(V_{\mathrm{ent}} + V_{\mathrm{rf}})$ and $\varepsilon_{\mathrm{min}} = \alpha(V_{\mathrm{ent}} - V_{\mathrm{rf}})$ assuming the localized state $\varepsilon(t) = \alpha(V_{\mathrm{ent}} + V^{\mathrm{rf}}\cos(2\pi f t))$. Here α is a conversion factor from the entrance voltage to the localized energy level of the QD. After simple algebra, we have the pumping condition for V_{ent}, $E_{\mathrm{U}}/\alpha - V^{\mathrm{rf}} < V_{\mathrm{ent}} < E_{\mathrm{L}}/\alpha + V^{\mathrm{rf}}$. Using this relationship, it is known that the 'tunneling blockade gap' ΔE_{UL} can be experimentally obtained from the formula, $\Delta V_{\mathrm{ent}} = -\Delta E_{\mathrm{LU}}/\alpha + 2V^{\mathrm{rf}}$ [8] where ΔV_{ent} describes the length of current plateau in V_{ent} axis. Plotting ΔV_{ent} as a function of V^{rf} gives $-\Delta E_{\mathrm{LU}}/\alpha$ as an intercept in $y-$axis.

The 2nd panel of Fig. 1(d) plots $\Delta E_{\mathrm{LU}}/\alpha$ as a function of V_{P}. As we are lack of informations on the conversion factor α, we deal with the scaled 'tunneling blockade gap' $\Delta E_{\mathrm{UL}}/\alpha$. $\Delta E_{\mathrm{LU}}/\alpha$ increases as a function of V_{P}, which is contrary to the f_c tendency. If we assume that the cutoff frequency f_c is due to some nonadiabatic effects, then we can speculate that there might exist a maximum speed of level-shift rate that determines f_c. Figure 2 plots $\Delta E_{\mathrm{LU}}/\alpha$ multiplied by f_c representing a maximum speed of QD level shift, $\alpha^{-1}(d\varepsilon/dt)_{\mathrm{max}} \equiv \Delta E_{\mathrm{LU}}/\alpha \times f_c$, as a function of relative variation of V_{P}, ΔV_{P} for three different samples, SA1, SA2 and SA3. Figure 1 corresponds to SA1. SA2 and

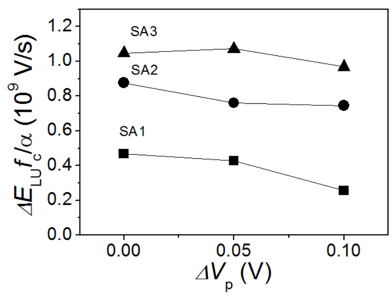

Fig. 2. Scaled 'tunneling blockade gap' $\Delta E_{\mathrm{UL}}/\alpha$ multiplied by f_c vs relative variation of plunger voltages ΔV_{P} for three different samples. Fig.1 corresponds to SA1.

SA3 also showed very similar characteristics as SA1 but with different values of δ_2, $\Delta E_{\mathrm{UL}}/\alpha$ and f_c (not shown here). As shown in Fig. 2, $\alpha^{-1}(d\varepsilon/dt)_{\mathrm{max}}$ values are different among three samples. But $\alpha^{-1}(d\varepsilon/dt)_{\mathrm{max}}$ for each sample does not vary much with respect to ΔV_{P}. At this moment as we don't know the value of the conversion factor α, we cannot confirm whether the value of $(d\varepsilon/dt)_{\mathrm{max}}$ to be constant irrespective of samples, or not. We need further study on this isssue.

III. Conclusion

We have observed the cutoff frequency f_c almost inversely proportional to the tunneling blockade gap ΔE_{UL} when the QD potential shape is controlled by a plunger gate. Our observations and discussions propose that there might exist a maximum speed of level-shift rate represented by f_c.

Acknowledgment

This work was supported by the Korea Research Institute of Standards and Science under the project "Convergence Science and Technology for Measurements at the Nanoscale," (Grant No. 16011060). MB was partially supported by the National Research Foundation of Korea (NRF) (2015R1A2A1A10056103).

References

[1] B. Kaestner, *et al.*, "Single-parameter nonadiabatic quantized charge pumping," *Phys. Rev. B.*, vol. 77, no. 15, pp. 153301-1 - 155311-6, April 2008.

[2] S.P. Giblin, *et al.*, "Towards a quantum representation of the ampere using single electron pumps," *Nature Comm.* 3:930 doi: 10.1038/ncomms1935, July 2012.

[3] Myung-Ho Bae, *et al.*, Precision measurement of a potential-profile tunable single-electron pump, *Metrologia* 52, pp. 195 - 200, Feburary 2015.

[4] M. W. Keller, "Current status of the quantum metrology triangle," Metrologia, vol. 45, no. 1, pp. 102109, Feb. 2008.

[5] M. Kataoka, *et al.*, "Tunable nonadiabatic excitation in a single-electron quantum dot," *Phys. Rev. Lett.*, vol. 106, pp.126801-1 - 126801-4, March 2011.

[6] M. Seo, *et al.*, "Improvement of electron pump accuracy by a potential-shape-tunable quantum dot pump," *Phys. Rev. B*, vol. 90, no. 8, pp. 085307-1 - 085307-5, Aug. 2014.

[7] V. Kashcheyevs and B. Kaestner, "Universal decay cascade model for dynamic quantum dot initialization," *Phys. Rev. Lett.*, vol. 104, no. 18, pp. 186805-1 - 186805-4, May 2010.

[8] B. Kaestner, *et al.*, "Robust single-parameter quantized charge pumping," Appl. Phys. Lett., vol. 92, no. 19, p. 192106, May 2008.