Robustness of Potential-Profile-Tunable Electron Pump

Ye-Hwan Ahn[1,2], Minky Seo[3], S.P. Giblin[4], M. Kataoka[4], Yunchul Chung[3], Nam Kim[1] and Myung-Ho Bae[1]

[1]Korea Research Institute of Standards and Science, Daejeon 34113, Republic of Korea
(mhbae@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]National Physical Laboratory, Hampton Road, Teddington, Middlesex TW11 0LW, United Kingdom

***Abstract* — We performed a robustness test of a potential-profile-tunable electron pump for various parameters. Tuning the entrance and exit gates, we measured a flat current plateau within the 2 μA/A uncertainty for a ~40 mV gate-voltage range at *B* ~ -14 T. For changes of *B*-field, the 2-μA/A plateau was obtained for -14 T < *B* < -12.7 T. The 2 μA/A plateau was also observed in the overlapped exit-gate voltage range over ~40 mV at *T* = 300 mK and 1.3 K. The robustness of the pumping demonstrates stable operation and a feasible way to construct parallel pumps.**

***Index Terms* — Measurement, measurement uncertainty, precision measurements**

I. INTRODUCTION

An electron pump is a promising candidate to realize the ampere according to the new SI definition [1]. The single-parameterized electron pump, based on a quantum dot (QD) formed on a GaAs/AlGaAs two-dimensional gas (2DEG) system with metal top-gates, has shown a high-speed operation at a pumping frequency of 1 GHz, generating a current as large as ~160 pA accurate to ~1 μA/A or better[2,3,4]. Here, we performed robustness tests for the gate-defined single-parameterized pump, which is designed to tune the potential shape for the QD by several split gates [3,5]. The measurements revealed that our pump is accurately quantized within the ~2-μA/A standard uncertainty of a typical measurement over finite ranges of tuning parameters such as gate voltages, *B*-field and temperature at pumping frequency f = 0.5 GHz, corresponding to ~80 pA. The robustness of the pump lays a foundation for the future redefinition of ampere [6] as well as providing a stable pump operation and a robust basis for increasing the current by running several pumps in parallel.

II. EXPERIMENTS AND DISCUSSION

A QD in a GaAs/AlGaAs 2DEG system was formed with three split gates and a trench gate crossing the split gates on the top GaAs layer as shown in Fig. 1(a). Positive V_T (~0.53 V) and V_P (~0.39 V) on the trench and plunger gates were applied to get a relatively deep potential well, which offers a larger charging energy resulting in a stable quantized current. The upper three finger gates were set to V_A ~ -1 V to push and squeeze the QD, resulting in a thicker potential barrier and relatively large charging energy, as indicated by a purple region in Fig. 1(a) [5]. The width of the wave packet of an electron inside the QD can be shrunk by *B*-field, which leads to a wider potential barrier width and higher accuracy [7]. With an rf biasing at f = 0.5 GHz and P = 6 dBm with a 3 dB attenuator into the entrance gate, we obtained quantized current steps in the pumped current (I_p) as a function of V_{ent} and V_{ext}, which are denoted by *nef* for each current plateau in Fig. 1(b). Here n is an integer and e is the elementary charge. To see details of the quantized steps, we replot I_p-V_{ext} (scattered points in Fig. 1(c)) at V_{ent} = -1.1 V.

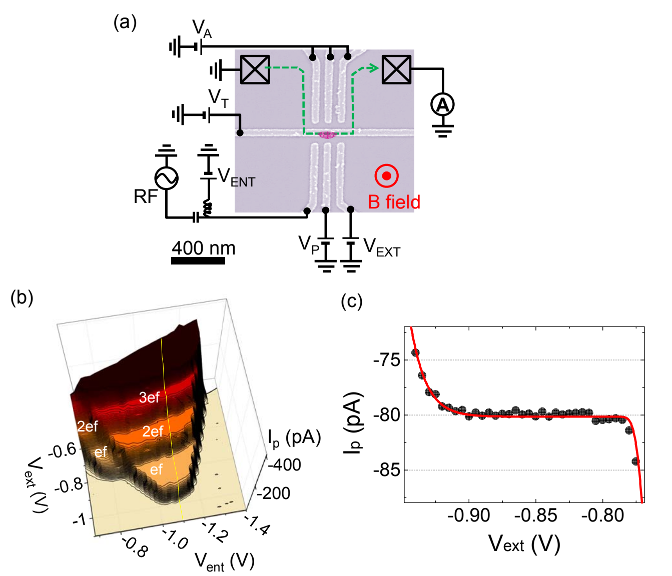

Figure 1. (a) SEM image of a representative potential-profile-tunable electron pump with experimental configuration. (b) Quantized current steps as a function of exit- and entrance-gate voltages (V_{ext}, V_{ent}) at B = -14 T, T = 0.3 K and f = 0.5 GHz (P = 6 dBm), where each step is denoted by *nef* with an integer number, n. (c) Pumped current, I_p (scattered points) as a function of V_{ext} at V_{ent} = -1.1 V, which is indicated by a yellow line in (b). A red curve is a fit result based on the decay-cascade model. Red points were obtained by the precision measurement.

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

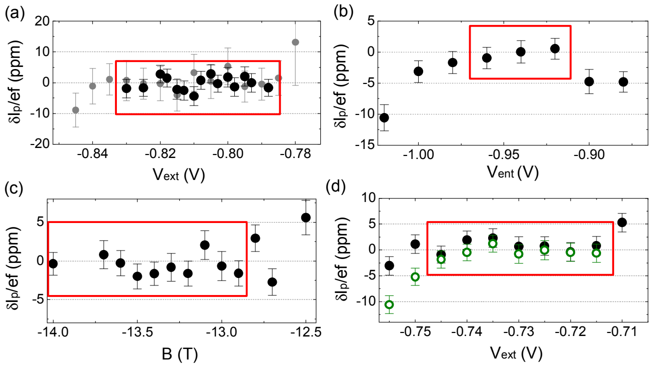

Figure 2. Relative deviation ($\delta I_p/ef$) from ef in μA/A as a function of (a) V_{ext} (grey points: 40 cycles, black points: 150 cycles), (b) V_{ent}, (c) B-field at $T = 0.3$ K, and (d) V_{ext} for $T = 0.3$ K (black solid points) and 1.3 K (green opened points).

The decay-cascade model (red line in Fig. 1c) [8] predicts that the current will be within 2 μA/A of ef over the range -0.821 V < V_{ext} < -0.79 V ($\Delta V_{ext} \sim$ 30 mV), where 2 μA/A is an upper limit of the total uncertainty in the precision measurement.

Figures 2(a) and 2(b) show the relative deviation ($\delta I_p/ef$) from ef in μA/A as a function of V_{ext} and V_{ent}, where $\delta I_p = I_p - ef$. Grey scattered points in Fig. 2(a) obtained with 40 on-off cycles [2,3] show the general trend of the quantized current, *i.e.*, a rapid deviation from ef with varying V_{ext} for a relatively positive $V_{\rm ext}$ (>-0.78 V) and a slow change for a relatively negative $V_{\rm ext}$ range (<-0.84 V) including a flat region for -0.835 V < $V_{\rm ext}$ < -0.785 V. We again performed the precision measurement with 150 cycles in the relatively flat region, shown as scattered black points, where we found the current equal to ef over the range -0.83 V < $V_{\rm ext}$ < -0.788 V (a red box), which agrees with the above prediction by the decay-cascade model with a slight off-set. The $\delta I_p/ef$ -$V_{\rm ent}$ in Fig. 2(b) also provides 2 μA/A plateau flatness for -0.96 V < $V_{\rm ent}$ < -0.92 V (a red box) at V_{ext} = -0.73 V, which was obtained with a different condition from Fig. 1(b).

We performed the robustness test by adjusting the B-field and temperature as shown in Figs. 2(c) and 2(d). In Fig. 2(c), 2 μA/A flatness was found for -14 T < B < -12.9 T (a red box).. In Fig. 2(d), there are two groups of black and green scattered points at T = 0.3 K and 1.3 K, respectively. A high temperature broadens the energy level in the QD and increases the back-tunneling probability of a loaded electron [9]. For 0.3 K < T < 1.3 K, the 2-ppm uncertainty range was found for -0.745 V < $V_{\rm ext}$ < -0.715 V (a red box) of $\Delta V_{\rm ext}$ = 30 mV. This result implies an important practical issue: a pumped He4 system at ~1.5 K can provide 2- μA/A accuracy over a finite range of gate voltages. Indeed, recent experiments on the potential-profile tunable electron pump at T = 4.2 K, even without B-field, provided the uncertainty < 2 ppm based on the decay-cascade analysis with low-resolution measurements [5].

III. Conclusion

We tested the robustness of the potential-profile tunable electron pump with variation of exit and entrance gates, B-field and temperature. Within a 2-μA/A uncertainty we found for $\Delta V \sim$ 40 mV for both $V_{\rm ext}$ and $V_{\rm ent}$ at T = 0.3 K, a B-field range of -14 T ~ -12.9 T, and $\Delta V_{\rm ext} \sim$ 40 mV at temperatures of 0.3 K and 1.3 K. Such wide parameter ranges are encouraging for the development of parallelized pumps [10].

Acknowledgement

This work was supported by the Korea Research Institute of Standards and Science (KRISS), and within the joint research project "Quantum Ampere" JRP SIB-07 within the European Metrology Research Program (EMRP). MB was partially supported by the National Research Foundation of Korea (NRF) (2015R1A2A1A10056103).

References

[1] J. P. Pekola, O.-P. Saira, V. F. Maisi, A. Kemppinen, M. Möttönen, Y. A. Pashkin et. al., , "Single-electron current sources: Toward a refined definition of the ampere," *Rev. Mod. Phys.*, vol. 85, no. 4, pp. 1421-1472, October 2013.

[2] S.P. Giblin, M. Kataoka, J.D. Fletcher, P. See, T.J.B.M. Janssen, J.P. Griffith et. al., "Towards a quantum representation of the ampere using single electron pumps," *Nature Comm.* vol. 3, pp. 930, doi: 10.1038/ncomms1935, July 2012.

[3] M.-H. Bae, Y.-H. Ahn, M. Seo, Y. Chung, J. D. Fletcher, S. P. Giblin et. al., Precision measurement of a potential-profile tunable single-electron pump, *Metrologia* 52, pp. 195-200, February 2015.

[4] F. Stein, D. Drung, L. Fricke, H. Scherer, F. Hohls, C. Leicht et. al., "Validation of a quantized-current source with 0.2□ppm uncertainty," Appl. Phys. Lett., vol. 107, no. 10, p. 103501, September 2015.

[5] M. Seo, Y.-H. Ahn, Y. Oh, Y. Chung, S. Ryu, H.-S. Sim et. al., "Improvement of electron pump accuracy by a potential-shape-tunable quantum dot pump," *Phys. Rev. B*, vol. 90, no. 8, pp. 085307, August 2014.

[6] S.P. Giblin et. al., "An accurate high-speed single-electron quantum dot pump," N. Jour. Phys., vol. 12, no. 7, pp.073013, July 2010.

[7] J. D. Fletcher, M. Kataoka, S. P. Giblin, S. Park, H.-S. Sim, P. See, et. al., "Stabilization of single-electron pumps by high magnetic fields," *Phys. Rev. B*, vol. 86, no. 15, pp. 155311, October 2012.

[8] 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.

[9] L. Fricke, M. Wulf, B. Kaestner, V. Kashcheyevs, J. Timoshenko, P. Nazarov et. al., "Counting statistics for electron capture in a dynamic quantum dot," Phys. Rev. Lett., vol. 110, no. 12, pp. 126803, March 2013.

[10] S. J. Wright, M. D. Blumenthal, M. Pepper, D. Anderson, G. A. C. Jones, C. A. Nicoll et. al., "Parallel quantized charge pumping," Phys. Rev.B, vol. 80, no. 11, pp. 113303, September 2009.