# Robustness of single-electron pumps at sub-ppm level

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***Abstract*—Single-electron pumps (SEP's) based on tunable barrier quantum dots show the most promise as high-precision nanoampere quantum sources. They are treated as a good candidate in the context of a quantum representation of the SI base unit ampere. A key point for such a realization is the robustness of operation. Here we show the invariance of current at a sub-ppm level against variation of magnetic flux density, bias voltage on source and drain and the entrance gate voltage.**

***Index Terms*—Current measurement, quantized current, redefinition of SI base units, single-electron pump.**

## I. Introduction

Non-adiabatic tunable barrier pumps operate by modulation of the quantum dot (QD) defining barriers. A current of $I = \langle n \rangle ef$ is produced with the average number of electrons transferred per cycle $\langle n \rangle$, the pumping frequency $f$ and the elementary charge $e$. The pump operating parameters can be tuned such that a fixed integer number of electrons is pumped per cycle with small error rates due to quantum mechanical processes. This kind of pumps shows most promise for the realization of the new SI base unit ampere [1]. In recent years lots of efforts have been made to verify accuracy by direct current measurements by both the enhancement of the measurement setup and the raise of the repetition rates [2], [3], [4]. The latest improvements were achieved using a recently developed ultrastable low-noise current amplifier (ULCA) [5], [6], [7] with a transresistance traceable to the quantum Hall resistance. The ULCA is also used for measurements shown in this paper. The current after conversion to voltage is then traced back to the Josephson effect. For further analysis we assume $R_K = h/e^2$ and $K_J = 2e/h$.

A promising advancement of SEP's are self-referenced current sources based on in-situ error detection [9]. For all approaches the impassivity against the main driving parameters is of prime importance. In this way, it is relevant for self-referenced current sources that shifts in the potential of source or drain do not influence the accuracy of the pump current. Generally, loading and unloading of possible traps inside the pumping structure should not change the pumping characteristic significantly. Furthermore, the independence of magnetic flux is of importance for integrated circuits where several pumps are operated simultaneously. For these reasons we verify the invariance of current against variation of entrance gate voltage, magnetic flux density and bias voltages applied to source and drain.

## II. Experiment

The device used for our experiments is a single-electron pump based on a GaAs/AlGaAs heterostructure shown in

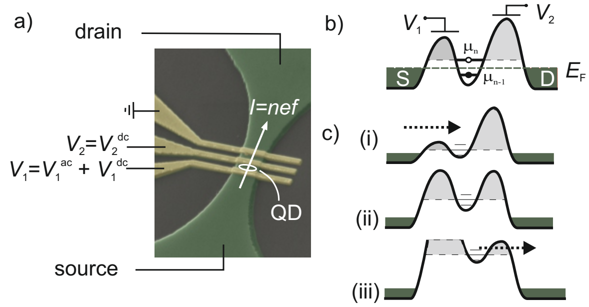


Fig. 1. (a) False-color SEM micrograph of a single-electron pump with descriptions. (b) Sketch of the dynamic QD which is electrostatically defined via top-gates. Fermi level and energy levels of the QD are indicated. (c) Process of electron transfer sketched in three phases, (i) loading electrons from the source lead, (ii) isolation of the quantum dot, and (iii) ejecting electrons to drain.

Fig. 1. On the one-dimensional etched channel three Ti/Au Schottky top-gates are deposited to form the QD. For this purpose negative dc-voltages $V_1^{\rm dc}$ and $V_2^{\rm dc}$ are applied to the gates. Fig. 2(b) sketches the potential landscape that is generated below the barriers. By modulating the entrance barrier height by an RF-signal $V_1^{\rm ac}$ from an arbitrary wave-generator the energy levels $\mu_{\rm n}$ from the QD are reduced below the Fermi level $E_{\rm F}$ and electrons can enter the dot. Further elevation of the entrance barrier lifts the energy levels, isolates the QD from source and ejects the electrons to drain in the next phase (cf. Fig. 1(c)). This pump mechanism leads to a clocked electron transfer and a current of $I = \langle n \rangle ef$.

All measurements presented in this contribution were performed at temperature $T = 0.1\,$K and for the same pump, but within different cooling cycles. The pulse shape used for all measurements was similar to the one described in [5] and unless otherwise stated at a pumping frequency of $f = 600\,$MHz. The following measurement was done at a magnetic flux of 12 T.

To reveal the independence of current against the variation in the entrance gate $V_1^{\rm dc}$ a characteristic contour-line plot was recorded, shown in Fig. 2(a). Naturally a cut in the direction of the exit gate voltage $V_2^{\rm dc}$ is analyzed and then measured with high precision in the area of the expected highest accuracy. Here, the current reaches the value of $I = 1ef \approx 96\,$pA as explained in [5] (Fig. 2(b) top). A fit gives an interval where a theoretical deviation of current $I$ from $ef$ is less then $0.01\,$ppm (cf. [10], [5]). Points inside this interval are averaged and result in an overall deviation from $ef$, determined with a statistical and systematical uncertainty. For our measurement only one cut in the $V_2^{\rm dc}$ direction was performed and the inflection

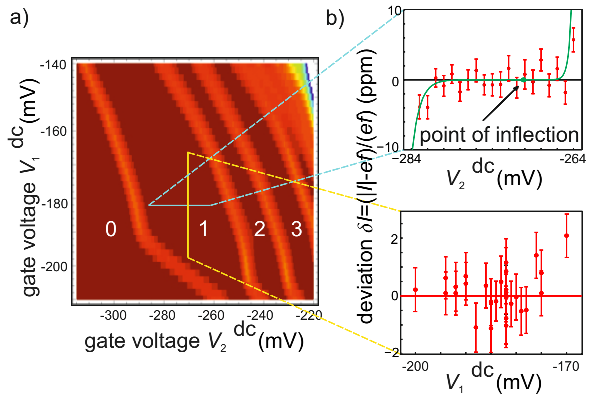


Fig. 2. (a) Contour-line plot of the deviation of current. Regions of 0, 1, 2, and 3 transferred electrons are labeled. (b) Precision measurements realized in regions marked in (a), diagrammed in deviation from $ef$. Error bars reflect Type A uncertainty ($k = 1$). Green graph shows a fit proposed in [10].

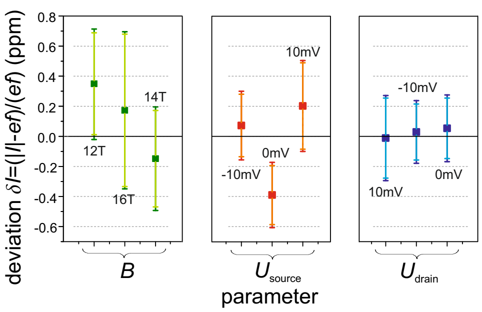


Fig. 3. Resulting deviation $\delta I$ from $ef$ derived from averaging a particularly chosen number of precision points such as shown in Fig. 2(b) for parameter variation of magnetic flux density $B$, bias voltage of source $U_{\text{source}}$ and drain $U_{\text{drain}}$. Light Error bars reflect Type A uncertainty, dark Error bars combined uncertainties (all for $k = 1$).

point calculated. Subsequently the exit gate voltage $V_2^{\text{dc}}$ was fixed at the inflection point and the entrance gate voltage $V_1^{\text{dc}}$ varied from $-200\,\text{mV}$ to $-170\,\text{mV}$ (cf. Fig. 2(b) bottom). The data show that in an interval of at least $10\,\text{mV}$ length around the starting point at $V_1^{\text{dc}} = -182\,\text{mV}$, the determined current values equal $ef$ within their statistical uncertainty. Averaging within an interval of $[-192\,\text{mV}\ ...\ -172\,\text{mV}]$ yields an average current deviation of $(0.052 \pm 0.208)\,\text{ppm}$ (total uncertainty, $k = 1$). From these data we can deduce that even trap charging processes inside our QD structure (typically appearing as shifts of the pump characteristics of $1 - 2\,\text{mV}$) should not influence the accuracy of the pump.

Further robustness tests were performed for different magnetic flux densities. For this purpose the procedure described explicitly in [5] was used. The current value was determined by averaging a small data-set of precision points around the inflection point of a cut in $V_2^{\text{dc}}$ direction from the characteristic contour-line plot. Fig. 3 images the obtained current values for $12\,\text{T}$, $14\,\text{T}$, and $16\,\text{T}$. Shown are the Type A uncertainties and combined uncertainties including a systematic error of $0.13\,\text{ppm}$. Thus all values equal $ef$ within their combined standard uncertainties, i.e. $k = 1$.

Variation in bias voltages on source (on drain) is performed at a frequency of $600\,\text{MHz}$ ($545\,\text{MHz}$). The magnetic flux density was $9\,\text{T}$ for both experiments. For the following measurements a reduced systematic uncertainty budget of $0.1\,\text{ppm}$ can be assumed due to improvements in the experimental setup. For voltages of $-10\,\text{mV}$ and $10\,\text{mV}$ the current values equal $ef$ within their total standard uncertainty. During this measurement campaign the outlier at no bias voltage can be explained by simple statistical distribution as it is in line with $ef$ for expanded total uncertainty ($k = 2$).

From the data shown in this paper an overall current value can be derived to $-0.001\,\text{ppm}$ $\pm 0.125\,\text{ppm}$ combined uncertainty while averaging all relevant precision points.

## III. Conclusion and Outlook

The demonstration of the universality of pump operation is relevant for all further efforts towards the new definition of the SI base unit ampere as the robustness of a realization is a strong requirement. The independence of bias voltages in particular is a necessary condition for the operation of self-referenced current sources. Generally, the parameter impassivity is important for the realization of integrated circuits where the parallel operation of single-electron pumps is aimed [9]. Still under progress are the investigations of frequency and driving mode.


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## References


[1] B. Kaestner and V. Kashcheyevs, “Non-adiabatic quantized charge pumping with tunable-barrier quantum dots: a review of current progress,” *Rep. Prog. Phys.*, vol. 78, no. 10, p. 103901, 2015.

[2] S. P. Giblin, M. Kataoka, J. D. Fletcher, P. See, T. J. B. M. Janssen, J. P. Griffiths, G. A. C. Jones, I. Farrer, and D. A. Ritchie, “Towards a quantum representation of the ampere using single electron pumps,” *Nat. Commun.*, vol. 3, p. 930, Jul. 2012.

[3] B. Kaestner, C. Leicht, F. Hohls, M. Götz, D. Drung, K. Pierz, F. J. Ahlers, and H. W. Schumacher, “Characterization of a GHz non-adiabatic single-electron pump using a cryogenic current comparator,” *CPEM 2012 Conf. Digest*, pp. 706–707, Jul. 2012.

[4] G. Yamahata, K. Nishiguchi, and A. Fujiwara, “Gigahertz single-trap electron pumps in silicon,” *Nat. Commun.*, vol. 5, p. 5038, Oct. 2014.

[5] F. Stein, D. Drung, L. Fricke, H. Scherer, F. Hohls, C. Leicht, M. Götz, C. Krause, R. Behr, E. Pesel, K. Pierz, U. Siegner, F.-J. Ahlers, and H. W. Schumacher, “Validation of a quantized-current source with 0.2 ppm uncertainty,” *Appl. Phys. Lett.*, vol. 107, no. 10, p. 103501, Sep. 2015.

[6] D. Drung, C. Krause, U. Becker, H. Scherer, and F. J. Ahlers, “Ultrastable low-noise current amplifier: A novel device for measuring small electric currents with high accuracy,” *Rev. Sci. Instrum.*, vol. 86, no. 2, p. 024703, Feb. 2015.

[7] D. Drung, M. Götz, E. Pesel, and H. Scherer, “Improving the traceable measurement and generation of small direct currents,” *Instrumentation and Measurement, IEEE Transactions on*, vol. PP, no. 99, 2015.

[8] B. Kaestner, V. Kashcheyevs, S. Amakawa, M. D. Blumenthal, L. Li, T. J. B. M. Janssen, G. Hein, K. Pierz, T. Weimann, U. Siegner, and H. W. Schumacher, “Single-parameter nonadiabatic quantized charge pumping,” *Phys. Rev. B*, vol. 77, no. 15, p. 153301, 2008.

[9] L. Fricke, M. Wulf, B. Kaestner, F. Hohls, P. Mirovsky, B. Mackrodt, R. Dolata, T. Weimann, K. Pierz, U. Siegner, and H. W. Schumacher, “Self-referenced single-electron quantized current source,” *Physical Review Letters*, vol. 112, no. 22, p. 226803, Jun. 2014.

[10] V. Kashcheyevs, and J. Timoshenko, “Modeling of a tunable-barrier non-adiabatic electron pump beyond the decay cascade model,” *CPEM 2014 Conf. Digest*, pp. 536–537, Aug. 2014.