Precision measurement of a potential-profile tunable single-electron pump

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Abstract

We performed a precision measurement of the current from a single-parameter electron pump, where the potential-profile for a quantum dot was manipulated by multiple top-metal gates. In an optimally tuned condition, driven with a sinusoidal-waveform microwave at \( f = 0.95 \text{ GHz} \), \( B = 11 \text{ T} \), and \( T = 0.3 \text{ K} \), the relative deviation of the pump current from \( e f \), \( \delta I_p/ef \equiv (I_p - e f)/ef \) was measured to be \((-0.92 \pm 1.37) \text{ ppm}\). Our experiment reproduces the current quantisation accuracy of a previous measurement of a single-parameter pump, but in a device fabricated using very different geometry, thereby indicating that accurate single-parameter pumping is insensitive to device details.

Keywords: single electron pump, quantum current standard, QD electron pump

1. Introduction

Quantum current-standard devices have been developed for realization of the quantum metrology triangle, which is expected to contribute to the redefinition of the ampere [1]. A promising candidate for the quantized current-standard is a single-parameter charge pump based on a quantum dot (QD) [2, 5], where the current output at each plateau satisfies the relation, \( I_p = nef \). Here, \( e \) is the elementary charge, \( f \) is the frequency of external microwave (MW) for a periodically modulating potential barrier (see figure 1(a)) and \( n \) is the number of electrons pumped for each MW cycle. Such charge pumps based on a single QD have been realised in various semiconducting nanostructures such as silicon nanowires [3, 4] and GaAs/AlGaAs two-dimensional electron gas (2DEG) systems [5–10]. The accuracy of one specific design of a GaAs/AlGaAs pump has been shown to be better than 1.2 ppm at a current of 150 pA [6], although this was an isolated result which has so far not been replicated on other designs of single-parameter pumps. It is clearly desirable to demonstrate that accurate charge pumping in single-parameter pumps is a universal phenomenon, which can be reproduced in another structure.

In this paper, we demonstrate accurate operation of a potential-profile-tunable QD-pump device made of multiple-top metal gates on a GaAs/AlGaAs 2DEG system. We measured the pump current using the same measurement setup as in [6], with a type \( B \) uncertainty, \( u_B = 1.2 \text{ ppm} \). We found that the pump current was equal to \( e f \) for \( 0.6 \text{ GHz} \leq f \leq 0.95 \text{ GHz} \), within the total uncertainty, \( u_T = 1.4 \text{ ppm} \).
of the initialization process in determining the pump accuracy, has been experimentally demonstrated by employing a tailored waveform for the electron loading stage [6] and by means of a single-charge detection technique experiment [7]. In the so-called decay-cascade model, the ratio between back-tunneling rates at the first excited state and the ground state $\Gamma_2/\Gamma_1 \equiv e^{\delta_2}$ determines the accuracy of the $n=1$ quantized current plateau. Thus $\delta_2$ can be treated as a practical figure of merit for the accuracy of $n=1$ quantized current, and a predictive tool for estimating the pump accuracy from the result of a rapid characterization measurement.

Generally, the ratio $\Gamma_2/\Gamma_1$ is determined by the potential barrier shape in 2 dimensions, charging energy of the QD and the wave-function of the electron trapped within the QD, all of which are a complicated function of the gate geometry and temporally changing gate fields. One approach to tuning $\Gamma_2/\Gamma_1$, is to employ a magnetic field to shrink the electron wave-function [8], as shown in figure 1(b). In this way, as described in detail in [9], $\delta_2$ increases from ~5 to >20 as a result of varying the B-field from 0 to 14 T at $f = 0.1$ GHz.

Recently, we showed that seven electrostatic gates can be used to tune the potential barrier shape as well as the charging energy of the QD, to tune the pump accuracy [10]. The tunability of the QD shape is a key difference from the pump developed in [6] that has only two top gates over an etched 2DEG strip. Direct manipulation of the potential profile for the QD has been achieved by applying negative multiple-gate fields to the QD, resulting in shift and reduction of the QD from its original location and size, respectively, as shown in figure 1(c) (also see figure 1(d) for the sample geometry). This results in the increase of the electron addition energy in the QD as well as the increase of the height and thickness of the QD potential barrier [10]. Using this technique, it was shown that $\delta_2$ increases from 10 to 18 for $f = 0.1$ GHz without B-field [10]. In this work, we use the combined effect of the magnetic and electrostatic confinement tunability to enhance the current quantisation accuracy.

3. Experimental set-up for evaluation of single-electron pump

A QD was formed in a GaAs/AlGaAs 2DEG system, 62 nm below the surface, with multiple-top metal gates as shown in figure 1(d), where a blue-colored region corresponds to the
QD. We lowered the temperature of the sample in a $^3$He system to 0.3 K under a bias-cooling condition, with a voltage of 0.4 V applied to all gates to reduce random telegraph noise [12], and keeping the source and drain electrodes grounded. The two quantum-point contacts (QPC) biased with voltages $V_{\text{ENT}}$ and $V_{\text{EXT}}$ were operated as tuning barriers for source and drain electrodes, respectively. The plunger and trench gates biased with voltages $V_P$ and $V_T$ were used to manipulate the potential-profile of the QD [10, 13]. We periodically modulated only the upper entrance potential using an MW bias, while both upper and lower gates were biased by dc voltages. Here, the microwave source (HP8341B) was synchronized to a 10 MHz reference signal derived from NPL’s frequency standard. Throughout all measurements, the source–drain channel was unbiased. For the high-resolution precision measurements, we used a ‘null detection technique’ with a reference current, $I_R$, which was produced by a $1 \, \text{G} \Omega$ standard resistor ($R_s$) and a dc-voltage source ($V_R$) as shown in figure 2(a). The measurement system is identical to that used for previous pump measurements [6], and a breakdown of the 1.2 ppm type B uncertainty is given in supplementary table S1 of [6]. The measurement protocol differs slightly from that in [6], in that the time for one on–off cycle was shortened to 16 s due to higher 1/f noise than the device used in [6], which was determined by an Allan deviation measurement (not shown). For example, figure 2(b) shows two on–off cycles for $f = 0.7 \, \text{GHz}$ pump operation, where a voltage $V_{\text{nd}}$ was measured across $R_s$ biased by $V_R$, and current $I_{\text{nd}}$ was obtained by difference between $I_R$ and $I_p$. Then, the value of $I_p$ was obtained by $\Delta I = \Delta V/R_s$, where $\Delta V$ and $\Delta I$ are mean differences of $V_{\text{nd}}$ and $I_{\text{nd}}$ between ‘On’ and ‘Off’ states for each cycle, respectively. Here, the first 5 points were neglected to reject the transient effect. All the data in this paper were obtained from a single device.

4. High-resolution precision measurements

Scattered points in figure 3(a) show the low-resolution measurement results for pump current $I_p$ as a function of $V_{\text{EXT}}$, showing quantized current plateaus, in an optimal tuning condition ($V_{\text{ENT}} = -0.4 \, \text{V}$, $V_A = -0.22 \, \text{V}$, $V_B = 0.15 \, \text{V}$, $V_T = 0.4 \, \text{V}$, $f = 0.7 \, \text{GHz}$, power $P = 6 \, \text{dBm}$ at the source output and perpendicular magnetic field $B = 11 \, \text{T}$). As the magnetic field was increased from $B = 0$, the plateau width improved as has been previously reported [6, 8, 9]. However, we did not observe consistent improvement of the plateau above 11 T. The integer numbers for the plateaus correspond to the $n$th current plateau satisfying $n \, e f$. The $n = 1$ current plateau at a certain $V_{\text{EXT}}$
Figure 3. Pump current ($I_p$) as a function of $V_{\text{EXT}}$ (scattered points: experimental result, solid curve: a fitted result based on the decay-cascade model with equation (1)) at $f = 0.7$ GHz under $B = 11$ T. (b) Relative deviation ($\delta I/ef$) from $ef$ in ppm as a function of an offset gate voltage scale, $\Delta V_{\text{EXT}}$ (scattered points: results of high-resolution precision measurement with 200 on–off cycles, dashed red curve: fractional deviation predicted by the decay-cascade model), where error bars express the measurement uncertainty, $u_\alpha$. The horizontal green line shows the average value of the sixteen points in the grey box region with an error bar indicating the total uncertainty $u_T$. (c) $\delta I/ef$ as a function of an offset gate voltage scale, $\Delta V_{\text{EXT}}$ (scattered points: results of high-resolution precision measurement with error bars of $u_\alpha$, dashed curve: relative deviation predicted by the decay-cascade model) for $f = 0.95$ GHz. The horizontal green line shows the average value of the twelve points in the grey box region with an error bar indicating $u_T$. (d) Summary of ($\delta I/ef$) with 7 h-long measurement for each point at $f = 0.6$ GHz (solid circles) and 0.7 GHz (open circles), and 3.5 h-long measurement for each point at $f = 0.95$ GHz (closed diamonds) to give total uncertainty, $u_T = 1.4$ ppm, which appears as error bars. The relative deviations are re-calculated with data obtained over a certain $V_{\text{EXT}}$ range (see blue-colored regions in (b) and (c)). For example, data points for $f = 0.7$ GHz indicated by ‘a’ and ‘b’ are re-calculated with all data obtained from $-0.016 \text{V} \leq \Delta V_{\text{EXT}} \leq -0.009 \text{V}$ and $-0.008 \text{V} \leq \Delta V_{\text{EXT}} \leq -0.001 \text{V}$ (8 points indicated by ‘a’ and ‘b’ in (b)), respectively.

range, is observed when a single electron is loaded into the QD. In this process, more than one electron can be loaded. To leave a single electron in the QD during a decoupling process, we used an analytic expression of the decay-cascade model for a single-parameter electron pump [11],

$$I_p = I_{ef} \sum_n \exp \left( -\exp \left( -\frac{V_{\text{EXT}} - \beta}{\alpha} + \ln \gamma_n \right) \right)$$

where $I_{ef} = ef, e = 1.602 176 565(35) \times 10^{-19} \text{C} \ (2010 \text{CODATA value of } e [14]), \beta$ is an off-set of $V_{\text{EXT}}$ and $\alpha$ is a coupling constant between $V_{\text{EXT}}$ and the corresponding energy shift in the QD. Here, $\delta_n$ is defined by $(\ln \gamma_n - \ln \gamma_{n-1})$. The red curve in figure 3(a) is a best fit-result with $\alpha = 0.014 \text{V}, \beta = -0.74 \text{V} and \delta_2 = 16.2$ based on equation (1), where the obtained $\delta_2$ corresponds to $\delta_2/ef = -2 \text{ppm at the point of inflection in } I_p(V_{\text{EXT}})$.

$V_{\text{EXT}} = -0.555 \text{V} [11]$ corresponding to $\Delta V_{\text{EXT}} = -0.004 \text{V} in figure 3(b) (\Delta V_{\text{EXT}} = -0.005 \text{V in figure 3(c)}).

Figure 3(b) shows a result of the high-resolution precision measurements (scattered points with error bars) at $f = 0.7$ GHz in the rectangle-box region in figure 3(a), where a mean value of the relative deviation of the pump current from $ef$ (in ppm), $\delta I/ef = \langle |I_p - ef|/ef \rangle$ is plotted as a function of $V_{\text{EXT}}$. Here, each point with Type A uncertainty $u_\alpha$ was obtained from 200 on–off null detection cycles (see figure 2). Figure 3(c) also shows the result (scattered points) at $f = 0.95$ GHz (power $P = 6.1 \text{dBm}$ at the source output). Some out-laying data points away from the main plateau region are due to device instability, discussed in the next section. It can be seen that the measured data is closer to $ef$ than the fit line, as has been reported previously [6]. In addition, we also performed high-precision measurements for $f = 0.6$ GHz (power $P = 6.4 \text{dBm}$) as shown in figure 4. Figure 3(d) shows a summary of $\delta I/ef$ for the three frequencies, with error bars indicating a total uncertainty $u_T$, averaged over $V_{\text{EXT}}$ for a $\delta I/ef$ region flat to within $u_T$ (see green error bars in figures 3(b) and (c)) with respect to their average values (see green horizontal lines in figures 3(b) and (c)), i.e. rectangle-boxed regions in figures 3(b) and (c), respectively. rectangle-boxed regions in figures 3(b) and (c) for $f = 0.7$ and 0.95 GHz, respectively. Here, the average values for $\delta I/ef$, with total uncertainties $u_T = \sqrt{u_A^2 + u_B^2}$ are ($\delta I/ef \pm u_T$) = ($-0.68 \pm 1.41$), ($-0.44 \pm 1.42$), and ($-0.92 \pm 1.37$) ppm for 0.6, 0.7 and 0.95 GHz, respectively. Here, $u_A$ and $u_B$ are uncertainties of types A (statistical) and B (systematic), respectively. This is one of the best current quantisation performance achieved experimentally at the 100 pA output level, as we cannot resolve any deviation of the pump current from the expected quantized value of $ef$ within the total measurement uncertainty.

5. Random telegraph noise versus accuracy

For top-gated field-effect devices defined in a GaAs/AlGaAs 2DEG system, the random telegraph noise (RTN) is an inevitable phenomenon [15]. One of possible origins of the RTN
is small leakage currents from the top-gate electrodes to the 2DEG channel [12]. Our device frequently showed unstable $I_p - V_{\text{EXT}}$ curves related to the RTN. Figure 4(a) shows such multiple $I_p - V_{\text{EXT}}$ curves at $f = 0.6$ GHz with $B = 11$ T, where each curve was obtained just before every data point taken by one-hour-long precision measurement shown in figure 4(b). The whole data set of figure 4 was obtained over a period of 90 h. The $I_p - V_{\text{EXT}}$ curves are clearly unstable during these measurements. We believe that the instability is due to multiple RTNs. We argue that these RTNs do not affect our precision measurements where the current is quantized. The curves in figure 4(a) are grouped into two sets, colored in green and blue. It can be seen that RTNs cause instability away from the current plateau, where the pumped current changes rapidly with gate voltage. However, the $I_p$ value is stable where the plateaus of the multiple curves overlap. This behavior is clearly seen in figure 4(c) where the $I_p$ values in figure 4(a) are plotted as a function of time for representative $V_{\text{EXT}}$ of (i) $-0.455$ V, (ii) $-0.51$ V and (iii) $-0.63$ V. Here, the data points are color-coded according to the line color in figure 4(a). The precision measurement data points in figure 4(b) were taken in the region of a yellow-shaded rectangle of figure 4(a). Here the data points are plotted either in green or blue, depending on the color of the low-resolution sweep (figure 4(a)) taken prior to the measurement. The green and blue dashed curves are fit results ($\delta_2 \sim 18$) with the left- and right-most curves in figure 4(a) based on the decay-cascade model. The green and blue precision data points follow the green and blue fit results, respectively. Figure 4(b) shows that, even in the presence of RTNs, the current value is stable where the current plateaus of the two curves overlap indicated by a red shaded rectangle. This shows that the pump exhibits stable operation over a sufficiently wide range of gate voltage to be unaffected by the presence of RTNs.

6. Conclusions

Together with the recent results from [6], our results show precision measurements for a single-parameter electron-pump formed on a GaAs/AlGaAs 2DEG system. For a current level of 150 pA in an asymmetric QD configuration, we measured the relative deviation of the pumped current from the expected quantized value $ef$ to be $(−0.92 \pm 1.37)$ ppm for $f = 0.95$ GHz and $B = 11$ T at $T = 0.3$ K. Our results show that accurate pump operation is a general property of the quantum-dot pump and is not dependent on specific design features. Furthermore, our gate design allows a greater degree of freedom to tune the shape of the dot potential, and the dot position can be moved to make the pump less sensitive to RTN. Our result is an important step in demonstrating the universality of the single-parameter electron pump mechanism.

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