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Parallel pumping of electrons

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Abstract. We present the simultaneous operation of ten single-electron turnstiles leading to one order of magnitude increase in current level up to 100 pA. Our analysis of device uniformity and background charge stability implies that the parallelization can be made without compromising the strict requirements of accuracy and current level set by quantum metrology. In addition, we discuss how offset charge instability limits the integration scale of single-electron turnstiles.

Realization of a standard for electrical current based on the discreteness of the electron charge e is one of the major goals of modern metrology. The theoretical basis for obtaining current $I = nef$ when n electrons are sequentially transferred at frequency f has been well known for more than two decades [1]–[5]. With multijunction devices it has been possible to demonstrate pumping with a relative accuracy of 10^{-8} up to picoampere level [6]. Although the accuracy is more than an order of magnitude better than what can be obtained from the present definition of ampere [7], the output current level is too small for applications apart from the capacitance standard [8]. In order to create sufficient current in this fashion with the desired accuracy, parallelization of multiple pumps is inevitable. In this paper, we demonstrate parallel electron pumps with quantized current plateaux. The parallelization is effected in up to ten devices,

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leading to a current level exceeding 100 pA. This is already enough for the closure of the so-called quantum metrological triangle [9, 10], which would then justify the current standard based on single electron transport.

The idea in the quantum metrological triangle is to probe the consistency of the current from an electron pump against two other quantum phenomena, namely resistance from the quantum Hall effect and voltage from the ac Josephson effect. This verification would yield a consistency check for two fundamental physical constants, the charge of electron e and Planck's constant \hbar , and enable one to define the SI units of electrical quantities directly from quantum mechanics. One option to make the verification is to use topologically defined current transformers to compare the current from the quantum Hall effect to the current from electron transport [10]. The quantum Hall effect requires a current of about $1 \mu\text{A}$ to obtain 10^{-8} relative uncertainty. The transformer can bring this current down to 100 pA, which until now has been impossible to obtain accurately using single-electron transport devices. Another method to make the comparison has been proposed [11], but currently at least a similar magnitude of current is required. To obtain higher current levels, various approaches have been studied [12]–[19], such as surface acoustic waves, superconducting devices, and semiconductor quantum dots, but the accuracy of these devices remains limited. Two separate semiconductor quantum dot devices have recently been operated in parallel [20]. The hybrid turnstile [21, 22] used in this work holds the promise of achieving extremely low pumping errors [23], similar to multijunction circuits. In addition, due to their simplicity, turnstiles can be scaled up to higher integration levels for parallel operation as they require only one tuning signal per device.

The scheme of parallel turnstiles is shown in a scanning electron micrograph in figure 1(a). In each of the repeated cells there is one individual device. It is a single-electron transistor (SET) where the tunnel junctions are formed by an overlap between superconducting leads and a normal metal island. These devices use the superconducting gap of the leads to provide the necessary hysteresis in operation instead of the series junctions used in earlier turnstiles [24]. With respect to parallelization, these devices require one independent dc gate voltage $V_{g,i}$ per device to compensate for the inevitable offset charges. The other signals, bias voltage V_b for setting the preferred tunnelling direction, and the RF gate voltage V_{RF} used for pumping, can be common to all the devices.

The circuits were fabricated on thermally oxidized Si chips using one photolithography and three electron-beam lithography steps. The chip size was $3.6 \text{ mm} \times 3.6 \text{ mm}$. Firstly, Ti/Au (5/95 nm) leads and contact pads were made using a standard lift-off photolithography process. The pads were located at the edges of the chip with the leads stretching to the chip centre, leaving a square-shaped $80 \mu\text{m} \times 80 \mu\text{m}$ area free for fine structures. Then, in this area, a 3/20 nm thick Ti/Au RF gate was deposited through a conventional soft mask formed in the bi-layer resist by electron-beam lithography. The RF gate was connected to one of the leads and covered in the next step by a patterned spin-on glass layer to isolate it from the turnstiles made above the RF gate. Finally, SINIS-type turnstiles were fabricated using two-angle deposition through a suspended mask created in a Ge layer using a tri-layer electron-beam process. The turnstile pattern was exposed in the top layer of polymethylmethacrylate and then, after development, transferred into the Ge layer by reactive ion etching in CF_4 gas. The undercut under the Ge mask was formed by etching of the bottom copolymer with oxygen in the electron-cyclotron-resonance machine. Deposition of the turnstile leads (Al) and islands (Au/Pd) was performed in an e-gun evaporator with an oxidation step in between, and measurements were performed immediately after the final deposition in a $^3\text{He}/^4\text{He}$ dilution refrigerator at temperatures below

0.1 K. Standard dc, and RF voltage sources were used with resistive dividers and attenuators to set the operation voltages. Current was measured with a room-temperature low-noise current amplifier.

The operation of a hybrid turnstile can be understood by considering the energy thresholds for single-electron tunnelling. The thresholds are determined by the externally controllable bias voltage V_b and gate offset $n_g = (C_{g,i} V_{g,i} + C_{RF,i} V_{RF})/e$, where $C_{g,i}$ and $C_{RF,i}$ are the coupling capacitances from the dc and RF gates to the island, respectively. In figure 1(b), we present the measured dc current and the thresholds of one of the devices on the V_b - n_g plane. The stable regions for the charge states $n = 0$ and 1 (red and black boxes, respectively) overlap, and ideally no dc current flows even at a finite bias voltage up to $V_b = 2\Delta/e$. Here Δ is the energy gap of the superconductor and n is the excess number of electrons in the island. The broad stability regions enable one to pump electrons sequentially by moving the gate offset n_g along the horizontal pumping trajectory shown as the solid blue line. To obtain high accuracy, the turnstile should spend enough time beyond the thresholds shown as solid lines, but should not cross the thresholds of backtunnelling shown as dashed lines. All devices should cross the forward tunnelling thresholds in concert while avoiding the backward tunnelling.

To test this uniformity in a parallel setup, four turnstiles were connected to a common drain while the source sides were left separate for individual characterization. Afterwards they were connected together to a common bias voltage source to demonstrate parallel pumping. The dc current–voltage characteristics of one turnstile are shown in figure 1(c), where the gate voltage is swept back and forth so that we obtain both extreme cases of gate open ($n_g = 0.5$) and gate closed ($n_g = 0.0$). Also, the current–voltage simulations for both of these cases are shown. These curves are calculated with sequential tunnelling approximation and are used to extract the device parameters that are listed in table 1. From pumping measurements, the rising edge to the first plateau was determined as the RF gate voltage $V_{r,m}$ for which the current is half the value at the plateau. The measured variation of $V_{r,m}$ between the devices was $\pm 7\%$. According to numerical simulations, this narrows the metrologically flat part of the plateau by about 10%.

In addition to the crucial parameters determining the thresholds, individual tunnelling resistances R_T of the turnstiles are obtained from simulations. This parameter, together with the total capacitance C and superconducting energy gap Δ , determine the maximum operation frequency of a turnstile [25]. However, for parallelization, there are no constraints on the similarity of the tunnelling resistances. The largest of them determines the maximum operational frequency of the system. For an aluminium-based device, the maximum current is limited to somewhat above 10 pA when a metrologically accurate operation is required [23, 25]. Parallel operation is therefore necessary to obtain higher current levels while simultaneously preserving high pumping accuracy.

After the characterization of individual turnstiles, they were connected in parallel and the pumping curves presented in figure 2 were measured. Here, we have changed the gate states of one (figure 2(a)), two (b), three (c) and four (d) devices simultaneously while keeping others at gate open. We thus obtain current plateaux where zero to eight electrons are transported within one cycle. This measurement demonstrates that we can fully control the dc gate states of each device. The gate state of each individual device i was extracted from the total current through all of the devices by sweeping gate voltage $V_{g,i}$. The gate open states correspond to the maximum values of current. Cross-coupling between the gates was less than 3% and hence only one iteration round after a rough setting of the gates was needed to obtain the gate states correctly to within 1%.

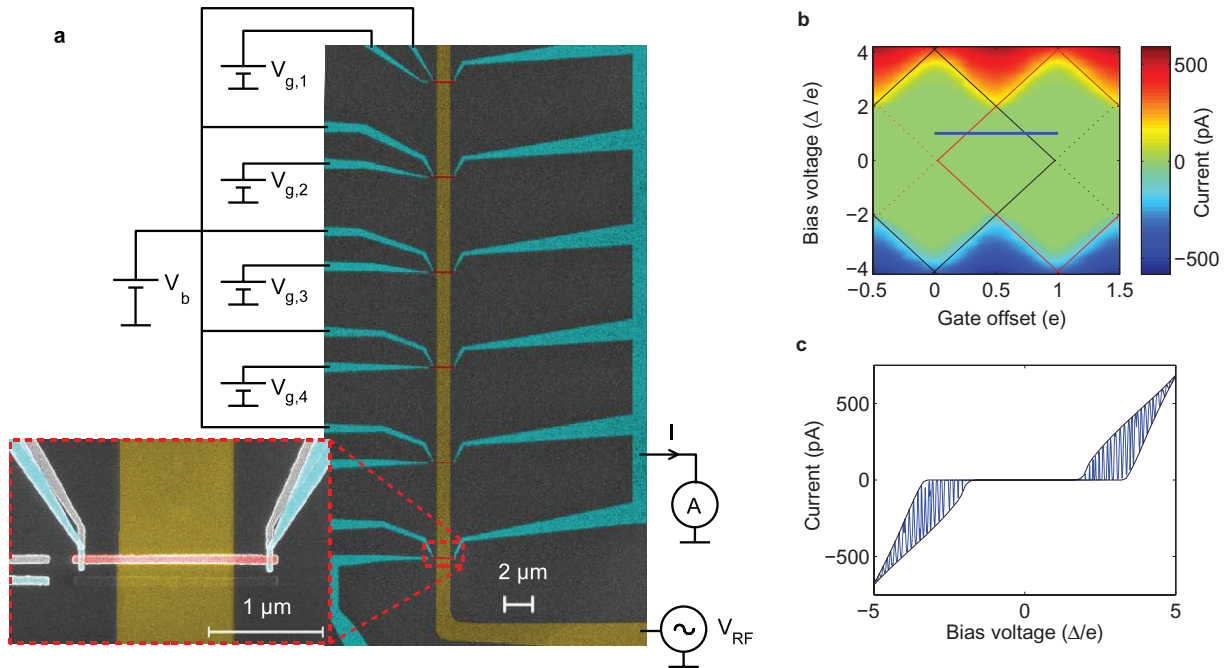


Figure 1. Parallelization scheme and the operation principle of a single turnstile. (a) Scanning electron micrograph of parallel turnstiles. Different metal layers are coloured for clarity. Normal metal islands (red) are placed on top of a common radio frequency (RF) gate (yellow). This gate is insulated from the islands by an SiO_x layer. Blue regions denote the superconducting aluminium wires. The tunnel junctions are formed under the islands by oxidizing aluminium. One gate line with dc voltage $V_{g,i}$ is needed for each of the devices, while the bias voltage V_b and the RF signal V_{RF} can be common to all turnstiles. (b) Stability diagram of turnstile D (see table 1) and the tunnelling thresholds for electron pumping. For tunnelling into the island the requirement is $-2E_c(n + 1/2 - n_g) \pm eV_b/2 \geq \Delta$ and for tunnelling out from the island it is given by $2E_c(n - 1/2 - n_g) \pm eV_b/2 \geq \Delta$. The upper (lower) sign corresponds to the junction that lies on the positive (negative) side of the bias. $E_c = e^2/2C$ is the charging energy of the island with total capacitance C and n is the number of excess electrons in the island. $n_g = (C_{g,i}V_{g,i} + C_{RF,i}V_{RF})/e$ is a normalized gate-induced offset charge used for controlling the energy thresholds. The green region inside solid black lines is stable for $n = 0$, while the green region inside solid red lines is stable for $n = 1$. Solid lines are thresholds for desired transitions during pumping while dashed lines correspond to backtunnelling in the wrong direction. The solid blue curve shows the ideal pumping curve with positive bias voltage at gate open. (c) Current–voltage characteristics of turnstile D. The gate offset charge is swept back and forth so that the envelopes correspond to the gate being open or closed. Simulations used to extract device parameters from these extremum cases are shown by black solid lines.

Next, to demonstrate reproducibility and robustness, ten turnstiles were operated similarly by a single RF drive. Two chips were used from different batches, with six turnstiles on one chip and four on the other. All ten devices were bonded to one common bias line and hence

Table 1. Parameters of the four turnstiles A–D. R_T and C_{RF} are estimated from the measurement data with an uncertainty of 1%. Δ and E_c/Δ are fitted with the help of numerical simulations to within 2% precision.

	$2R_T$ (k Ω)	Δ (μ V)	E_c/Δ	C_{RF} (aF)	$V_{r,m}$ (mV)
A	490	213	1.03	25.3	3.82
B	580	214	1.10	23.5	3.60
C	610	214	1.10	24.7	3.83
D	742	215	1.16	23.4	4.12

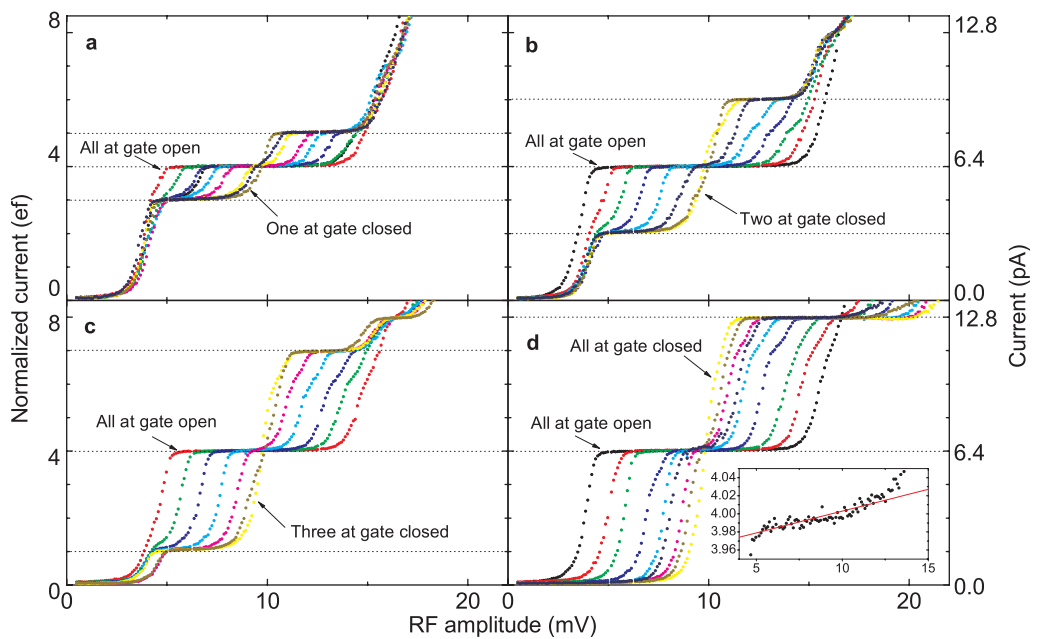


Figure 2. Parallel pumping of four turnstiles at $f = 10$ MHz. From (a) to (d), one to four devices are tuned between gate open and gate closed states, respectively, while the rest of the turnstiles are kept at gate open. This yields plateaux where 4 or $4 \pm N$ electrons are pumped in each cycle, where N is the number of tuned devices. The case $N = 4$ shows pumping curves similar to those of a single turnstile but with four times higher current. The inset in panel (d) shows a zoom where all devices are pumping one electron in a cycle. The solid red line is a linear fit which gives a plateau resistance of 500 G Ω with respect to RF voltage. The flatness of the plateau per turnstile is similar to what was observed for individual turnstiles. The accuracy of the measurements was limited by the drift of the current amplifier to the 10 fA level. The bias voltage was set to 200 μ V during the measurements.

no preliminary characterization of individual devices was made. The results for different bias voltages are shown in figure 3. This setup yields 104.1 pA at the first plateau with a pumping frequency of 65 MHz, which demonstrates a current level large enough to close the quantum metrological triangle [10]. In the present experiment, the number of parallel devices was limited by the number of dc lines available.

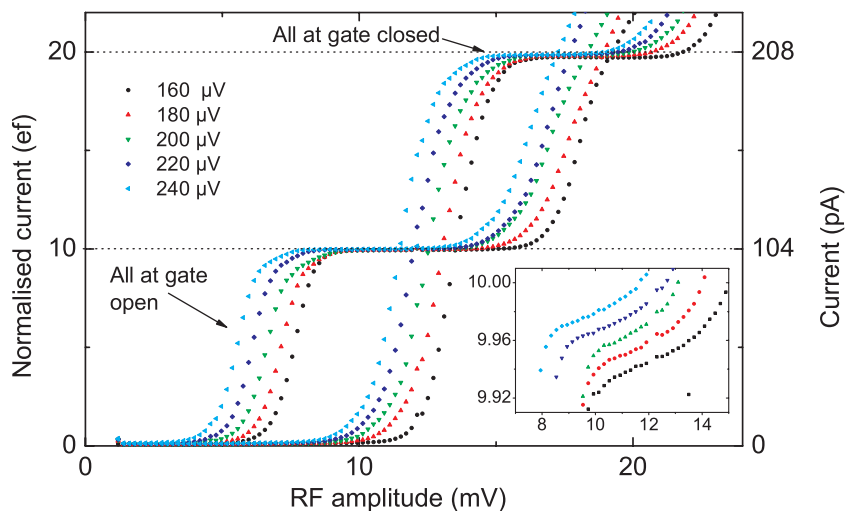


Figure 3. Ten turnstiles working at $f = 65$ MHz at different bias voltages. All turnstiles are set to either gate open or gate closed state. The current at the first plateau is approximately 104.1 pA. The inset shows a close-up of the first plateau. The estimated uncertainty of the current scale, based on the calibration of the pre-amp, is of the same order as the observed deviations from $I = 10 ef$.

In more general terms, the number of devices that can be operated in parallel simultaneously is determined by the offset charge stability. The strategy of a pumping experiment is to first set the gate of each turnstile, then perform the pumping measurement, and afterwards check the offset charges again. If they are not within the limits, one discards the data. It is worth noting that, unlike deviations in device parameters, the positive and negative changes in offset charge yield errors in pumping current in the same direction, and these types of error do not then average out with many devices as is the case for parameter deviations. To study the stability of the ten devices, the dc gate modulation was measured as a function of time for each of the turnstiles simultaneously. The time for one cycle was chosen to be 10 min, which was equal to the time required to measure the data of one curve in figure 2. The gate stability for a typical turnstile is shown in figure 4(a). From the measured data, histograms of the offset charge changes were determined for each of the devices, as shown in figure 4(b). Moreover, in the inset a histogram for the corresponding maximum change of the ten turnstiles is presented. From this we obtain a 73% probability of obtaining valid data with this measurement setup, as described in the caption. Additionally, we can estimate the maximum number of turnstiles operable in parallel to be 17 in the present case, which would yield an efficiency of 50%. By making the measurement period smaller, one could increase the number of devices as they have less time to get offset. We estimate that the measurement period can be decreased by one or two orders of magnitude. This will allow one to increase the number of parallel devices accordingly. Also, different materials or fabrication methods can provide smaller drifts and hence allow a larger integration scale. In our devices, the typical spectral density of charge noise followed the relation $S_q(f) = \alpha^2/f^2$ in the observed frequency range $f = 1 \mu\text{Hz} - 1 \text{mHz}$ with $\alpha = 10^{-6} e\sqrt{\text{Hz}}$. The magnitude is somewhat similar to previously reported values [26, 27]. We note that even better performance with no drifts has been observed for metallic single-electron devices previously [28, 29]. If such an improvement could be reliably achieved, one

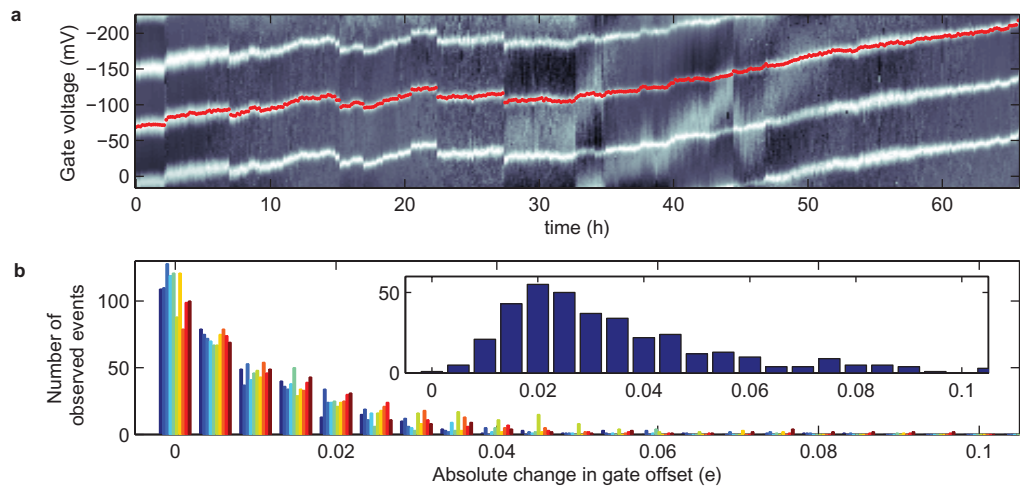


Figure 4. Stability of offset charges. (a) Gate modulation of one of the turnstiles as a function of time. The light/dark areas correspond to maximum/minimum current. The red dots show one of the gate open states, which is changing due to variations in the offset charges. These data are obtained as one set within sequential sweeping of the gate charges of the ten turnstiles. These ten sweeps are then repeated every 10 min. (b) A histogram of the changes in the offset charge between each sweeping set. The different colours denote different individual devices. In the inset, a histogram of the largest change in each set is shown. The total number of sweeps per turnstile is 410. Although for individual devices the changes are peaked at zero, for ten turnstiles it is more likely that at least one of the devices has changed by a few per cent. To obtain an estimate for the maximum number of devices that can operate in parallel, we assume that the offset charge changes are independent as the average correlation coefficient between the devices was 0.12. This gives a lower limit for the probability of having N turnstiles in correct gate states as $p_N = p_1^N$, where p_1 is the probability of having one turnstile in a correct state. The flatness of the theoretical current plateaux is such that with the observed 10% variation in tunnelling thresholds we can still tolerate a 5% change in gate offsets. With the measured data, this will lead to $p_1 = 0.96$ and $p_{10} = 0.71$. This is consistent with the value $p_{10} = 0.73$ obtained from the data in the inset of (b). Therefore the requirement for efficiency of $p_N \geq 0.5$ will limit the number of parallel turnstiles to $N = 17$ according to the presented data.

could further increase the number of parallel devices. However, for ten turnstiles and the present measurement time, this improvement is not required.

The main result of the present work is the controlled operation of parallel electron pumps. The stability of offset charges was studied and it is shown to allow more than ten parallel devices to be operated without significantly compromising the accuracy. These devices are prominent in fulfilling the strict accuracy requirements for closure of the quantum metrological triangle, and as the outcome of this work we show that the obtained current level achieves this. The flatness of the plateaux is preserved in parallel operation. Moreover, references [22, 30] and our recent

unpublished work suggest that the sub-gap leakage, which is the remaining error source, can be significantly decreased by proper design of the electromagnetic environment.

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