Accuracy of electron counting using a 7-junction electron pump

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We have operated a 7-junction electron pump as an electron counter with an error per pumped electron of 15 parts in 10^9 and an average hold time of 600 s. The accuracy and hold time are sufficient to enable a new fundamental standard of capacitance. We compare the measured accuracy of the pump as a function of pumping speed and temperature with theoretical predictions based on a model which includes stray capacitance. © *1996 American Institute of Physics.* [S0003-6951(96)03138-5]

The Coulomb blockade of electron tunneling in small junctions makes possible electrical devices which manipulate individual electrons.[1] One such device, the electron pump,[2] consists of a chain of metal islands separated by tunnel junctions, with a gate electrode coupled capacitively to each island. A sequence of voltage pulses applied to the gates manipulates the Coulomb blockade at each junction to pass a single electron along the chain. Because the current produced by the pump in its present form is small (about 1 pA), we have focused on using the pump as an electron counter. The pump can be used to place an accurate number of electrons on a capacitor, thus enabling a new standard of capacitance based on measuring the voltage produced by a known charge.[3] The proposed standard requires pumping $\sim 10^8$ electrons onto a 1 pF capacitor with an uncertainty in the number of electrons of ± 1. Thus the pump must have an error per pumped electron of about 1 part in 10^8, or 10 parts per billion (ppb). The pump must also have a small leakage rate when it is turned off (the hold mode) so that the charge on the capacitor remains fixed while the voltage is measured. In previous work,[4] a 5-junction pump was operated with an error per electron of about 500 ppb and a hold time of about 10 s. The 7-junction pump described in this letter has an error per electron of 15 ppb and a hold time of about 600 s. This device brings electron counting to the level of accuracy needed to make the new capacitance standard competitive with existing standards. Design, fabrication, and operation of the pump and accuracy measurements over a range of pumping speed and temperature are described below.

To maximize the Coulomb blockade and thus minimize errors, the pump must be designed with small junctions to reduce junction capacitance, small islands to reduce island self-capacitance, and a substrate with a small dielectric constant to reduce stray capacitance. For small islands, cross capacitance to all nearby conductors must also be considered. When a voltage V_g is applied to a single gate, the nearest island is polarized with a charge, but some polarization also occurs on neighboring islands. This cross capacitance effect can be eliminated by electronically adding a fraction of the applied voltage, with opposite polarity, to the neighboring gates. When the fractions are adjusted properly, through gain potentiometers in a special circuit, each islands can be polarized separately.[4] However, adjusting the gains for exact cancellation is difficult if the cross capacitance is too large, so the layout of islands and gates must be designed carefully. Based on capacitance calculations for several geometries, we chose the layout shown in Fig. 1.

We fabricated the pump on a fused quartz substrate using the two-angle evaporation of Al through a PMMA bilayer mask patterned by electron beam lithography.[5] We used a scanning force microscope to obtain images of completed devices (as in Fig. 1) without any apparent damage to the tunnel junctions.

The electrical circuit used to study the pump is shown in Fig. 2. The pump was connected to an external island, shown by heavy lines, which had a stray capacitance of about 20 fF. An electrometer[1] (also based on small tunnel junctions) monitored the voltage V_p on the external island. A cryogenic switch, consisting of a needle on a magnetically controlled lever, provided contact to a metallic pad on the external is-

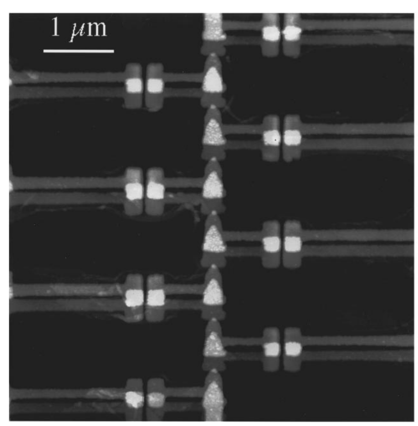

FIG. 1. Scanning force microscope image of the pump. The junctions are located at the bright spots where the tip of each island overlaps the island above it. (The false gate structures at the top right- and bottom left-hand side ensure that the two end junctions receive the same dose during electron beam lithography as the other junctions.)

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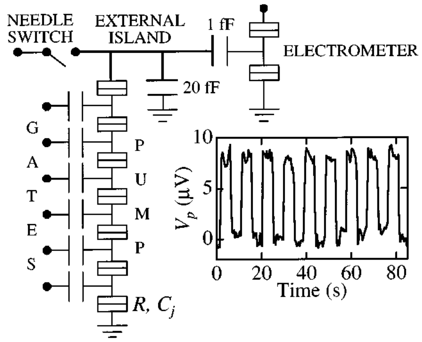

FIG. 2. Schematic of the circuit used to study the pump. All components except the needle switch were fabricated on a single chip. The entire circuit was placed in a copper box attached to the mixing chamber of a dilution refrigerator. Coaxial lines entering the box were heavily attenuated (gates) or filtered (others). The plot shows V_p vs time when pumping $\pm e$ with a wait time of 4.5 s between electrons.

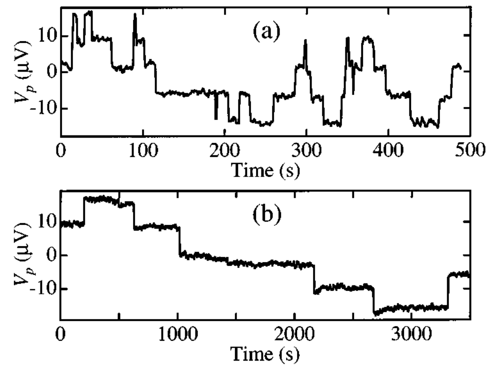

FIG. 3. Pump voltage vs time showing individual error events. (a) Pumping $\pm e$ at 5.05 MHz, average error per electron=15 ppb. (b) Hold mode, average hold time ≈600 S. $T_{mc}=35$ mK for both plots.

land. We closed the switch to measure the current–voltage curve of the pump, adjust the cross capacitance cancellation gains, and calibrate the electrometer. We opened the switch to detect intentionally pumped electrons or errors. The plot in Fig. 2 shows V_p versus time for the $\pm e$ pumping mode in which one electron is repeatedly pumped on and off the external island. Each step of 7.6 μV corresponds to a change in the island charge of e.

In determining various device parameters, we assume that all junctions in the pump have the same resistance R and capacitance C_j. From the current–voltage curve of the pump at large bias, we find $R=470$ kΩ± 14 kΩ and a Coulomb gap voltage $V_{\mathrm{gap}}=1.46$ mV± 0.1 mV (with dc gate voltages tuned for maximum gap). To obtain C_j from V_{gap}, we use an approximate model in which all capacitances other than C_j are represented by a capacitor C_{gnd} from each island to ground.[6] This ''ground capacitance model'' can be used to calculate analytically the energy of the system for any sequence of tunneling events. The model predicts $V_{\mathrm{gap}} = 7e/2C$ where $C = C_j + C_{\mathrm{gnd}}$. Based on a numerical calculation of V_{gap} that explicitly includes all calculated capacitances for the layout of Fig. 1, we take $C_{\mathrm{gnd}}=0.06$ fF.[7] Thus, we infer that $C_j=0.27$ fF$\pm m0.02$ fF from the measurement of V_{gap}. By pumping e, $2e$, $3e$, *etc.*, onto the external island, we determined that a charge of e changed the voltage across the pump by 7.6 μV± 0.5 μV. From this we infer a total external island capacitance of 21 fF± 1.5 fF.

Two *in situ* adjustments were required to achieve the desired sequence of island charge polarizations which pumps each electron.[4,8] First, the cross capacitance cancellation gains were adjusted. Using the fact that V_p at constant current bias is e-periodic in the charge polarization on any island, we adjusted the gains so that a change in the charge on any island by a multiple of e had no effect on V_p vs V_g for any of the gates.[4] The cross capacitance depends only on geometry, so this adjustment was needed only once. Second, dc bias voltages were added to the gates to compensate for offsets due to random background charges. The dc biases were adjusted to minimize the error rate while pumping. This was done by increasing the bias on a given gate until the error rate increased noticeably, decreasing the bias until the error rate increased again, and using the average bias as the optimal setting for that gate. The difference between the two settings where errors increased was typically $0.5e$. The dc bias adjustment for all six gates took only 10 min to complete, but it had to be repeated whenever changes in the background charges affected the pump accuracy. The optimal dc biases were typically stable (within $\pm 0.05e$) for a few hours, implying the same stability time for the background charges. The stability time fluctuated between less than 1 hour and tens of hours over the course of five weeks at a refrigerator temperature of 35 mK to 200 mK, with a trend toward more stable behavior over time.

We measured the accuracy of the pump by pumping in the $\pm e$ mode and recording V_p versus time as shown in Fig. 3(a). The pumping rate was much faster than the electrometer could respond, so V_p versus time is constant except for the jumps of 7.6 μV which signal individual errors. From the average time per error of 13 s and the pumping rate of 5.05 MHz we find an error per pumped electron of 15 ppb. We measured the leakage rate in the hold mode by recording V_p versus time with the gates pulses turned off as shown in Fig. 3(b). Each jump in this figure is one electron leaking through the pump and the average hold time is 600 s. When the background charges were stable, we were able to achieve similar results for pumping accuracy and leakage rate each time we tuned the dc biases as described above. Our best results were an error per electron of 10 ppb and an average hold time of about 900 s. A 7-junction electron trap with a maximum (not average) hold time of about 7000 s has been reported elsewhere.[9] As was found for the 5-junction pump,[4] our results are many times worse than predicted by theories of thermal activation and cotunneling.[8] We return to this discrepancy after describing the dependence of the errors on pumping speed and temperature.

The custom electronics used to operate the pump allowed us to adjust the pump time t_p needed to complete six gates pulses and the wait time t_w between electrons. Figure 4 shows the dependence of pump accuracy on t_p and on the overall pumping rate $1/(t_p+t_w)$. The main plot shows that the error per electron was independent of t_p at large t_p, but rose as t_p was decreased. This rise is expected, since the time each junction is biased to allow tunneling must be long compared to RC to avoid errors due to missed tunneling events.[10]

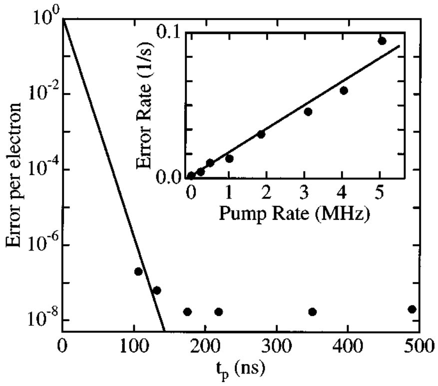

FIG. 4. Pump accuracy vs time to pump each electron. The speed of the electronics used to create the gate pulses limited the experiment to $t_p \geqslant 100$ ns. The line is Eq. (1) with $a=0.021$. Inset: error rate vs overall pump rate $1/(t_p+t_w)$ for $t_p=175$ ns. The line represents a constant error per electron of 16 ppb. $T_{mc}=35$ mK, $V_p \approx 0$ for both plots.

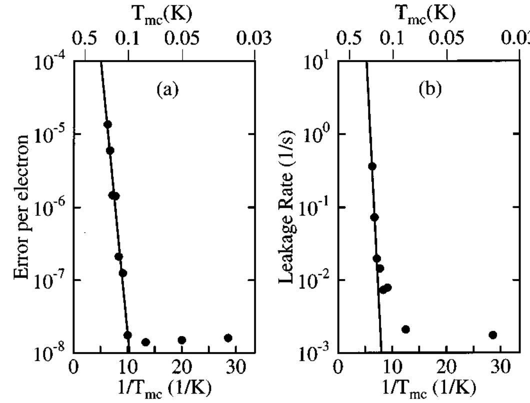

FIG. 5. Temperature dependence of (a) pumping accuracy and (b) leakage rate in the hold mode. Thermal smearing in the electrometer prevented measurements at $T_{mc}>160$ mK. $V_p \approx 0$ for both plots.

The expected form for the error per electron due to missed tunnel events is[8]

$$\epsilon_t = \exp(-a t_p / RC). \tag{1}$$

Since Eq. (1) gave a good fit for the 5-junction pump,[4] we use it to fit the data in Fig. 4 (constraining the fit to include the point $t_p=0$, $\epsilon_t=1$) and infer $a=0.021\pm0.005$. A simple theoretical analysis[8] in which every unwanted tunneling event leads to an error predicts $a=0.015$. A more complete dynamical analysis[8] predicts $a=0.039$. The inset of Fig. 4 shows the error rate versus overall pumping rate when t_p is fixed and t_w is varied. The linear scaling in this plot demonstrates that the overall pumping rate can be adjusted without affecting the error per electron.

Figure 5 shows the dependence of pumping accuracy and leakage rate on mixing chamber temperature T_{mc}. We first discuss the behavior at high temperature, where both the error per electron and the leakage rate increase exponentially. The theoretical expressions for errors due to thermally activated processes are[8]

$$\epsilon_{\text{th}} = b\ \exp(-\Delta E_p / k_B T) \quad \text{(pumping)}, \tag{2}$$

$$\Gamma_{\text{th}} = \frac{d}{RC} \exp(-\Delta E_h / k_B T) \quad \text{(hold mode)}, \tag{3}$$

where T is the electron temperature in the pump. The prefactors b and d and the energy barriers ΔE_p and ΔE_h can be predicted using the ground capacitance model. For our pump parameters we expect

$$b \approx 0.7, \quad d \approx 0.05$$

$$\Delta E_p = 2.0\ \text{K} \pm 0.2\ \text{K}, \quad \Delta E_h = 3.4\ \text{K} \pm 0.3\ \text{K}.$$

Fitting Eq. (2) to the data in Fig. 5(a) gives $b \approx 0.5 (0.2 < b < 1.3)$ and $\Delta E_p = 1.7\ \text{K} \pm 0.1\ \text{K}$. For the leakage rate we were not able to measure many decades of exponential behavior, so we assume the predicted prefactor $d=0.05$ and adjust ΔE_h to match the exponential part of the data, which gives $\Delta E_h = 3.3$ K. The measured hold mode energy barrier is consistent with the predicted value, while the measured pumping energy barrier is somewhat smaller than predicted. This is not surprising, since optimal pumping requires that pulse height and shape, cross capacitance cancellation, and dc biases all be properly adjusted, whereas the hold mode is only affected by the dc biases.

At low temperature, both the error per electron and the leakage rate are independent of T_{mc}. One possible explanation is that the pump temperature T is not equal to T_{mc} for $T_{mc} < 100$ mK. However, estimates of power dissipation due to the electrometer and to electrons passing through the pump indicate that heating in the pump is negligible. Furthermore, the electrometer continued to cool below 50 mK, indicating that the substrate and leads have adequate heat sinking. Another explanation is that a different, temperature-independent error mechanism dominates at low temperature. One such mechanism is photon-assisted cotunneling, which was suggested as an explanation for the anomalously large error of the 5-junction pump.[11] We are currently performing experiments to identify the error mechanism at low temperature.

In summary, we have used a 7-junction electron pump to count electrons with an error per electron of 15 ppb. With this device, electron counting has advanced from a novel laboratory phenomenon to a process that is accurate and reliable enough to be the basis for a new metrological standard of capacitance.

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