SUPPORTING INFORMATION

An accurate single-electron pump based on a highly tunable silicon quantum dot

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I. BIDIRECTIONAL PUMPING

As discussed in the main article, by using two driving voltages we can obtain quantized current in either direction. The potential landscape experienced by the electrons in this configuration can be modelled by

$$\begin{aligned}\varphi_{\mathrm{BL}}(t) &\propto \alpha_{\mathrm{BL/BL}}[V_{\mathrm{BL}} + \widetilde{V}_{\mathrm{BL}}\sin(2\pi ft)] + \alpha_{\mathrm{BL/PL}}[V_{\mathrm{PL}} + \widetilde{V}_{\mathrm{PL}}\sin(2\pi ft + \Delta\phi)] + \alpha_{\mathrm{BL/BR}}V_{\mathrm{BR}}\\ \varphi_{\mathrm{PL}}(t) &\propto \alpha_{\mathrm{PL/BL}}[V_{\mathrm{BL}} + \widetilde{V}_{\mathrm{BL}}\sin(2\pi ft)] + \alpha_{\mathrm{PL/PL}}[V_{\mathrm{PL}} + \widetilde{V}_{\mathrm{PL}}\sin(2\pi ft + \Delta\phi)] + \alpha_{\mathrm{PL/BR}}V_{\mathrm{BR}}\\ \varphi_{\mathrm{BR}}(t) &\propto \alpha_{\mathrm{BR/BL}}[V_{\mathrm{BL}} + \widetilde{V}_{\mathrm{BL}}\sin(2\pi ft)] + \alpha_{\mathrm{BR/PL}}[V_{\mathrm{PL}} + \widetilde{V}_{\mathrm{PL}}\sin(2\pi ft + \Delta\phi)] + \alpha_{\mathrm{BR/BR}}V_{\mathrm{BR}}\end{aligned} \tag{S1}$$

where the α factors are constants representing the couplings between gates and electrons at different positions. Thus, the effective phase differences between the individual potentials are functions of $\Delta\phi$, $\widetilde{V}_{\mathrm{PL}}$ and $\widetilde{V}_{\mathrm{BL}}$. Hence, the direction of the electron transfer can be experimentally controlled by tuning these variables, independently of the drain–source bias that can be conveniently left at zero. In the measurements shown in the main article, we have $\widetilde{V}_{\mathrm{BL}} \gg \widetilde{V}_{\mathrm{PL}}$, so that the transfer occurs from source to drain irrespective of the choice of $\Delta\phi$. This happens because the left barrier

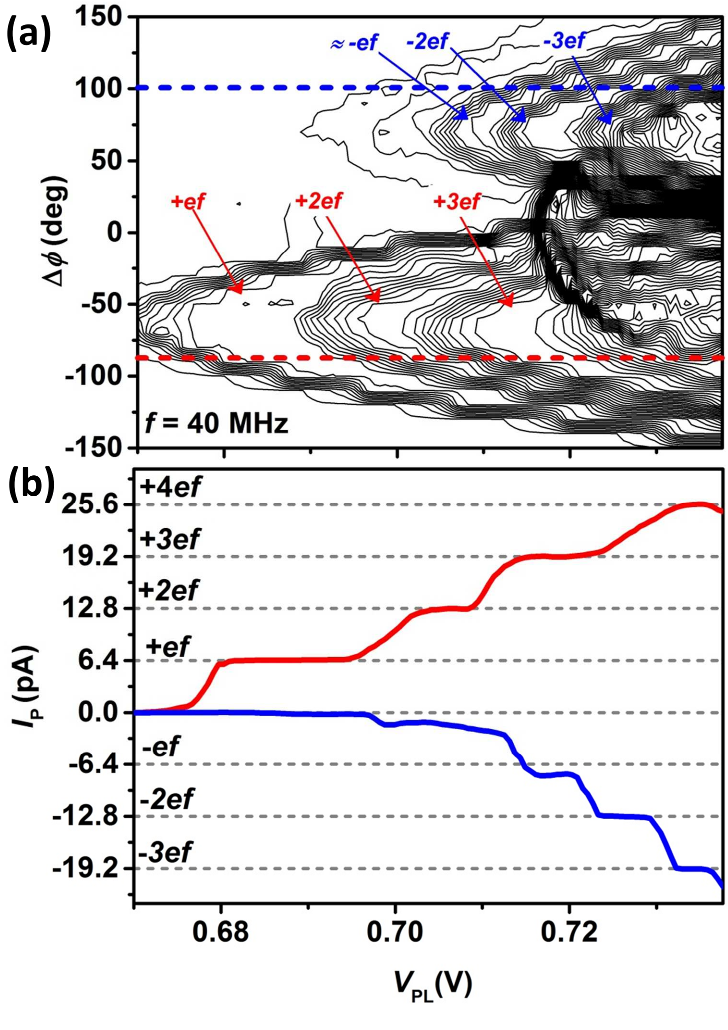

Figure S1 (a) Pumped current obtained with the two-parameter drive at 40 MHz as a function of V_{PL} and $\Delta\phi$ for $\widetilde{V}_{\mathrm{PL}}/\widetilde{V}_{\mathrm{BL}} = 0.71$, $V_{\mathrm{C1}} = 0$ V and $V_{\mathrm{C2}} = 0.35$ V. Contour lines are in steps of 500 fA. (b) Pumped current as a function of V_{PL} for $\Delta\phi = 100$ deg (in blue) and $\Delta\phi = -86$ deg (in red). Traces taken from (a) as indicated by dashed lines.

dynamics dominate and define a pumping protocol similar to the single sinusoidal drive of Fig. 1(c) and (e) of the main article. By contrast, in Fig. S1 we report data where bidirectional pumping takes place upon modification of $\Delta\phi$. For these measurements $\widetilde{V}_{\mathrm{PL}} \approx \widetilde{V}_{\mathrm{BL}}$ and the way the two waveforms combine is primarily dictated by their phases. We note that the quantization at negative currents does not appear as good as for the positive direction. We attribute this behaviour to the fact that the input barrier cannot be controlled as efficiently for the negative current as for the positive, since no drive signal is directly applied to BR.

II. EFFECT OF CONFINEMENT BIAS ON CHARGING ENERGY

As we discuss in the main article, gates C1 and C2 are utilized to control the planar confinement of the quantum dot. A convenient way of demonstrating the effectiveness of these gates is the evaluation of the dot charging energy, E_{C}, for different values of V_{C1} and V_{C2}. In our MOS structure, the vertical extension of the electron gas induced at the $\mathrm{Si/SiO_2}$ interface is very little affected by the bias, and typically these regions are modelled as two-dimensional electron gases[1]. Therefore, any variation in the total capacitance of the quantum dot, C_{Σ}, has to occur via a modification of the planar extension of the dot itself. This results in a change in the charging energy according to the relation $E_{\mathrm{C}} = e^2/C_{\Sigma}$. In Fig. S2(a) and (b), we compare the Coulomb diamonds of the dot in the multi-electron regime for two different confinement configurations. We observe that, for a fixed number of electrons in the dot (N), E_{C} increases from ≈ 3.2 meV to ≈ 5.0 meV with decreasing V_{C1} and V_{C2}. This ultimately demonstrates that gates C1 and C2 can

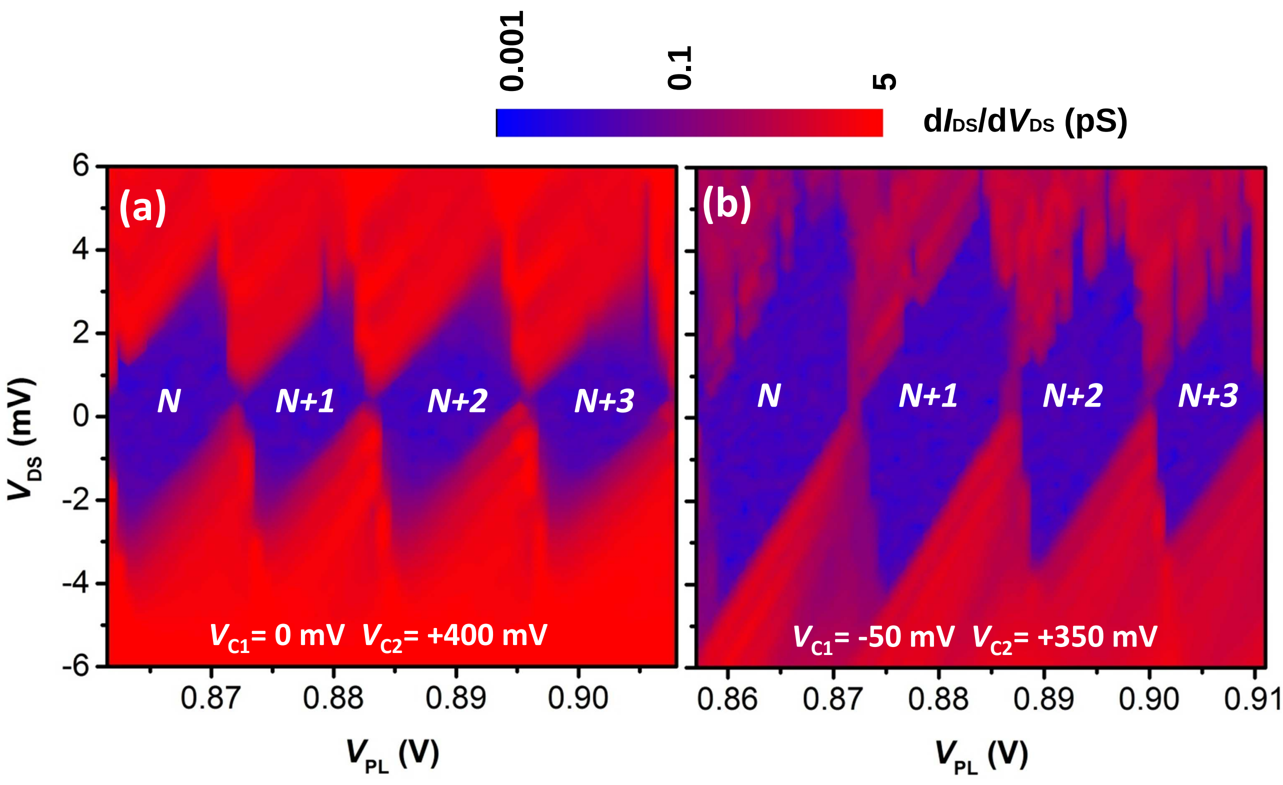

Figure S2 Differential conductance of the quantum dot in the multi-electron regime as a function of the plunger gate voltage and the drain–source bias for (a) $V_{\mathrm{C1}} = 0$, $V_{\mathrm{C2}} = 400$ mV, (b) $V_{\mathrm{C1}} = -50$ mV, $V_{\mathrm{C2}} = 350$ mV. For both datasets $V_{\mathrm{BL}} = 820$ mV, $V_{\mathrm{BR}} = 816$ mV. No driving signals are applied to the gates.

be used to control the size of the dot.

III. QUANTIZATION ROBUSTNESS

Any system that is aimed at quantum metrological applications, should be able to provide a stable and quantized output for a comfortably large range of all the adjustable parameters. In our experiments, we work with a multi-dimensional parameter space that needs to be iteratively scanned to yield the best current quantization. When one considers that in our experiments the drain–source bias is typically set at zero and the reservoir gates, $V_{\rm SL}$ and $V_{\rm DL}$, are kept at fixed positive bias, the number of variables can still vary from 6 for the single-parameter drive (namely, $V_{\rm C1}$, $V_{\rm C2}$, $V_{\rm PL}$, $V_{\rm BL}$, $V_{\rm BR}$, $\tilde{V}_{\rm BL}$) to 8 for the double-parameter drive (where $\Delta\phi$ and $\tilde{V}_{\rm PL}$ come into play). Although a detailed study of the dependence of the pump accuracy on these parameters is beyond the scope of this work, in Fig. S3 we report the results of a preliminary study. The measurement results shown are obtained with the same null detection configuration as discussed in the main article but with much faster integration time ($\approx$ 4 s per data

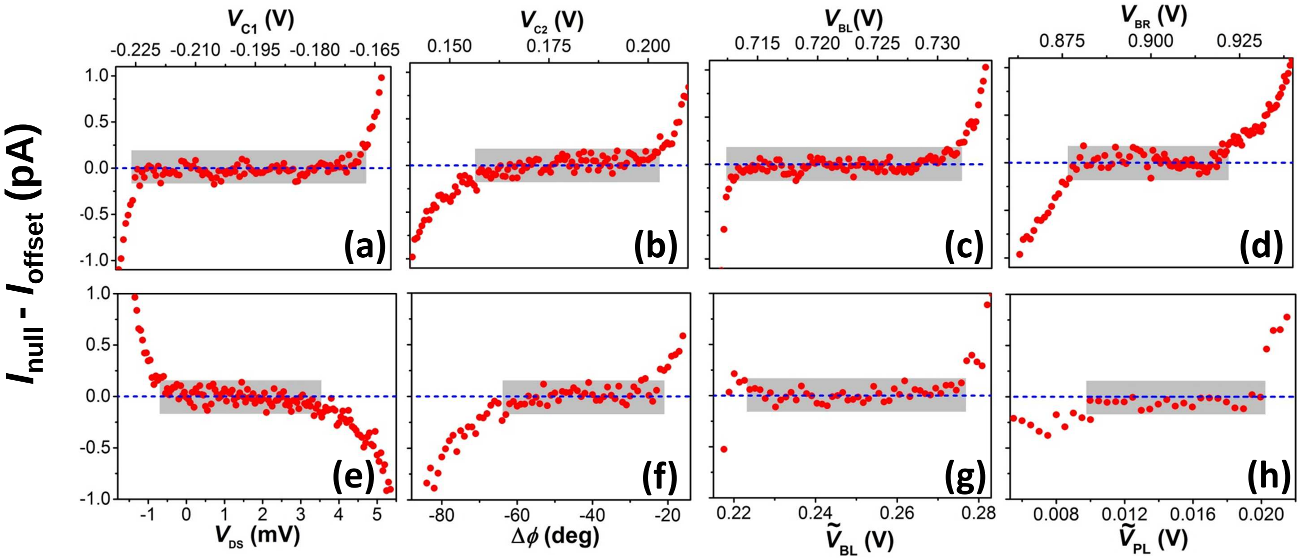

Figure S3 Coarse null measurements of the pumped current at 0.5 GHz as a function of (a) $V_{\rm C1}$, (b) $V_{\rm C2}$, (c) $V_{\rm BL}$, (d) $V_{\rm BR}$, (e) $V_{\rm DS}$, (f) $\Delta\phi$, (g) $\tilde{V}_{\rm BL}$, and (h) $\tilde{V}_{\rm PL}$. A fixed offset current $I_{\rm offset}$ = 550 fA is subtracted from each trace instead of taking readings for multiple ON-OFF cycles. The integration time for an individual data point is 4 s. Dashed lines are guides for the eye to highlight the zero current level. The grey shaded areas indicate the parameter ranges for which the deviation of the current from the expected value falls within $\pm$160 fA.

point). Moreover, they are taken as individual sweeps of the parameter of interest, rather than as the mean of multiple readings over subsequent ON-OFF cycles. Despite these limitations, we find that each experimental variable produces a current plateau in a sufficiently large range to allow simultaneous adjustments of other parameters. Due to the modest averaging time in these measurements, the dominant component of the uncertainty is of random type.

References

[1] Zwanenburg, F. A. *et al.* Silicon quantum electronics. *Rev. Mod. Phys.* **85**, 961 (2013).