Supplementary information: Gigahertz single-electron pumping in silicon with an accuracy better than 9.2 parts in 10^7

Gento Yamahata,[1] Stephen P. Giblin,[2] Masaya Kataoka,[2] Takeshi Karasawa,[1] and Akira Fujiwara[1]
[1)] *NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato Wakamiya, Atsugi, Kanagawa 243-0198, Japan*
[2)] *National Physical Laboratory, Hampton Road, Teddington, Middlesex TW11 0LW, United Kingdom*

A. Device fabrication process

The Si wire on a 400-nm-thick buried SiO_2 was patterned using electron beam lithography, followed by the thermal growth of a 30-nm-thick gate oxide. Then, n-type polycrystalline-Si lower gates (G1, G2) with a length of 40 nm were formed. The spacing between G1 and G2 is 100 nm. After the chemical-vapor-deposition growth of a 50-nm-thick inter-layer SiO_2, a wide n-type polycrystalline-Si upper gate was formed. Finally, n-type source and drain regions were formed by ion implantation with the upper gate used as a mask. The width and thickness of the Si wire are about 15 nm.

B. Measurement temperature

The temperature is measured using a thermometer in the cryostat. The reading of the thermometer during the high-accuracy measurements [Fig. 3(b) and Fig. 4 in the main text] are listed in the supplementary table 1.

C. Rough estimation of $E_{\rm add}$

When the barrier shape is parabolic, $\delta = E_{\rm add}/kT_0$ at the tunneling regime, where k is the Boltzmann constant and T_0 is a characteristic temperature determined by the curvature of the barrier and the effective mass of the charge carriers. To estimate $E_{\rm add}$ from δ, we need to know T_0. Typically, T_0 is less than 20 K because we have observed temperature dependence of δ in a similar device at more than 17 K[1]. If $T_0 = 10$ K, $E_{\rm add}$ is about 19 meV at 1 and 2 GHz, and about 8 meV at 6.5 GHz. The order of these values is similar to that of the previous observation[2]. For precise estimation, we need temperature dependence measurements.

D. Detail of the on-off measurement

To turn on and off $I_{\rm P}$, we changed the power of $V_{\rm RF}(t)$ between the pumping condition and -20 dBm (the minimum power of the HP 83623B); under the latter condition, $I_{\rm P} = 0$ because of the high exit barrier and very small modulation of the entrance barrier. Simultaneously, $I_{\rm R}$ is also turned on and off by changing the voltage applied to the standard resistor ($V_{\rm R} \sim efR$ and $V_{\rm R} \sim 0$ at the on-state and off-state, respectively). To eliminate a transient effect due to a low pass filter with a bandwidth of 0.7 Hz in the current amplifier, we ignore the first 15 points (corresponding to about 6 s) in each cycle, which are indicated by blue dots in Fig. 3(a) in the main text. The parameters of the on-off measurements are listed in the supplementary table 2. Note that the voltmeters were operated with an integration time of 10 power line cycles and auto zero enabled, so each reading took 0.4 seconds.

E. Type-A uncertainty $U_{\rm A}$

We chose the integration time to make the contribution of $U_{\rm A}$ much smaller than $U_{\rm B} = 0.88$ ppm. If we increase the integration time, it may be possible to reduce the contribution of $U_{\rm A}$. Since the ten data points in the yellow region in Fig. 3(b) in the main text are scattered in roughly 2 groups whose respective means differ by a statistically significant amount, we cannot neglect a possibility of a drift or slope (the origin is so far not clear). Therefore, we estimated $U_{\rm A}$ from the standard error of the mean of the ten data points; $U_{\rm A} = {\rm SD}/\sqrt{10} = 0.27$ ppm, where SD is the standard deviation of the ten points. Long continuous measurements at a fixed pump operating point are clearly required to investigate possible drifts of the pump current at the sub-ppm level.

References

[1] G. Yamahata, T. Karasawa, and A. Fujiwara, Appl. Phys. Lett. **106**, 023112 (2015).
[2] G. Yamahata, K. Nishiguchi, and A. Fujiwara, Appl. Phys. Lett. **98**, 222104 (2011).

Fig. 3(b)	Fig. 4 ($B = 0$)	Fig. 4 ($B = 14$)
1.27 K ($V_{\rm EXIT} = -1.255$)	1.38 K ($V_{\rm EXIT} = -1.315$)	1.32 K ($V_{\rm EXIT} = -1.315$)
1.25 K ($V_{\rm EXIT} = -1.25$)	1.45 K ($V_{\rm EXIT} = -1.31$)	1.19 K ($V_{\rm EXIT} = -1.31$)
1.24 K ($V_{\rm EXIT} = -1.24$)	1.66 K ($V_{\rm EXIT} = -1.305$)	1.21 K ($V_{\rm EXIT} = -1.305$)
1.30 K ($V_{\rm EXIT} = -1.23$)	1.46 K ($V_{\rm EXIT} = -1.3$)	1.38 K ($V_{\rm EXIT} = -1.3$)
1.25 K ($V_{\rm EXIT} = -1.22$)	1.68 K ($V_{\rm EXIT} = -1.295$)	1.38 K ($V_{\rm EXIT} = -1.295$)
1.31 K ($V_{\rm EXIT} = -1.21$)	1.68 K ($V_{\rm EXIT} = -1.29$)	1.39 K ($V_{\rm EXIT} = -1.29$)
1.31 K ($V_{\rm EXIT} = -1.20$)	1.66 K ($V_{\rm EXIT} = -1.285$)	1.39 K ($V_{\rm EXIT} = -1.285$)
1.35 K ($V_{\rm EXIT} = -1.19$)	1.69 K ($V_{\rm EXIT} = -1.28$)	1.17 K ($V_{\rm EXIT} = -1.28$)
1.38 K ($V_{\rm EXIT} = -1.18$)	1.69 K ($V_{\rm EXIT} = -1.275$)	1.34 K ($V_{\rm EXIT} = -1.275$)
1.25 K ($V_{\rm EXIT} = -1.175$)	1.60 K ($V_{\rm EXIT} = -1.27$)	1.39 K ($V_{\rm EXIT} = -1.27$)
1.25 K ($V_{\rm EXIT} = -1.1725$)	1.69 K ($V_{\rm EXIT} = -1.265$)	1.39 K ($V_{\rm EXIT} = -1.265$)
1.29 K ($V_{\rm EXIT} = -1.17$)	1.69 K ($V_{\rm EXIT} = -1.26$)	1.35 K ($V_{\rm EXIT} = -1.26$)
1.32 K ($V_{\rm EXIT} = -1.1675$)		1.3 K ($V_{\rm EXIT} = -1.255$)

Supplementary Table 1. Measurement temperatures during the high-accuracy measurements.

	Fig. 3(b)	Fig. 4 ($B = 0$)	Fig. 4 ($B = 14$)
Time to obtain a single data point in the cycle	$\sim$ 0.4 s		
Points per cycle	100		
Cycle time	$\sim$ 40 s		
Number of cycle	200	60	80
Integration time of each point	$\sim$ 130 min	$\sim$ 40 min	$\sim$ 50 min
Total duration of cycles after discarding initial points	$\sim$ 90 min	$\sim$ 30 min	$\sim$ 40 min

Supplementary Table 2. Parameters of the on-off measurements.