THE ROBUSTNESS AND UNIVERSALITY OF TUNABLE-BARRIER ELECTRON PUMPS

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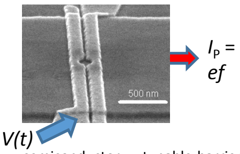
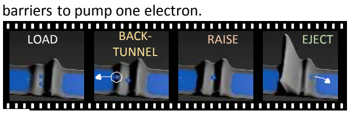
1. The tunable-barrier electron pump

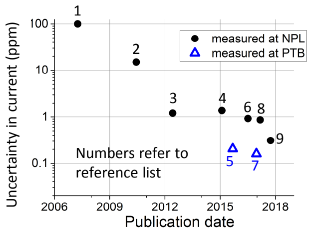


The semiconductor tunable-barrier electron pump is a candidate for a **primary current standard**. It generates a current by moving electrons one at a time in response to a periodic control voltage at frequency *f*

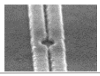
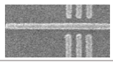
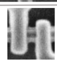
Electron pump research has driven dramatic improvements in small current metrology (graph at right, refs 3 and 10).

Below: modulation of electrostatic potential barriers to pump one electron.



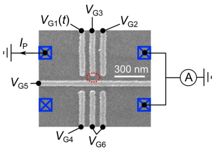


2. Pumps measured at NPL

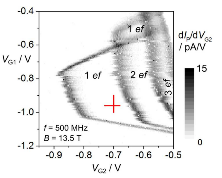
SEM image	Fabrication Institute	Material	Number of control gate voltages	References
	UNIVERSITY OF CAMBRIDGE	GaAs	**2**	[3]
	KRISS	GaAs	**6** (2 gates connected)	[4,8]
	UNSW	Si	**7**	[9]
	NTT	Si	**3** (including top gate)	[6]

Panel 4 also summarises precision measurements made at **PTB**, on PTB-designed GaAs pumps – see refs. **5** and **7**.

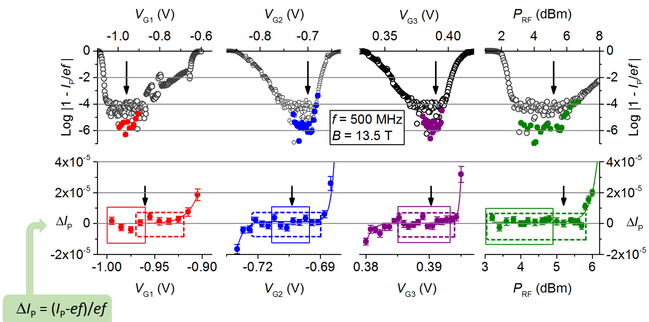
3. Robustness



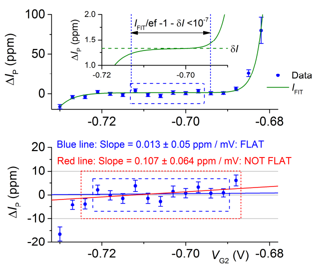
Below: Pump map. Cross indicates optimal working point



We can change any of the control parameters of the KRISS pump: V_{G1}, V_{G2}, V_{G3} or P_{RF} **without changing the pump current**, within an uncertainty of around 2 ppm per data point. Data in this panel taken from **ref. [8]**. See also ref. [7] for another robustness study.



A **plateau** can be defined with respect to a fit -in this case, a sum of two exponentials [ref. 11] with an offset δI. Alternatively, linear fits can establish a range of data where the slope is less than the fitting uncertainty.



4. Universality

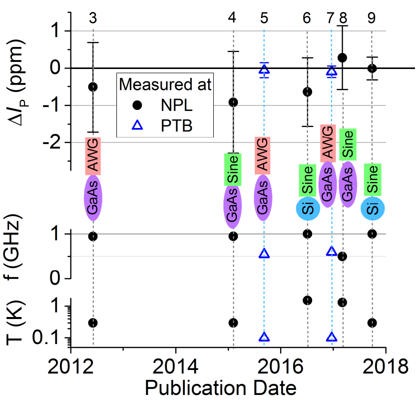
Does the pump mechanism work in pumps made from different materials, with different designs?

For 7 studies on optimally tuned electron pumps at NPL and PTB, we plot:

- Pump current ΔI_P
- Drive frequency *f*
- cryostat temperature *T*

Also indicated are the material used to make the pump (**Si or GaAs**) and whether the drive signal was a **Sine Wave** or from an Arbitrary Waveform Generator (**AWG**).

Numbers along the top of the plot refer to the reference list



5. Conclusions

Robustness:
We have shown robustness at the 1-2 ppm level of one design of pump to changes in 4 parameters; 3 gate voltage and the RF drive power.

Universality:
We have measured **4 different designs of pump**, 2 each using GaAs and Si technology. They all have current equal to *ef* within uncertainty of 1 ppm or less when optimally tuned.
Our best measurement, **0.27 ppm on a silicon pump @ 1 GHz**, can be compared with the best measurement on a GaAs pump, **0.16 ppm @ 600 MHz**, ref. 7.

Next:
Direct comparison of two different pumps.
Guidelines for electron pumps as primary realisation of ampere.

References:

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[9] R. Zao et al, arXiv: 1703:04795, *Submitted to Physical Review Applied*
[10] D. Drung et al, *Review of Scientific Instruments* **84**, 024703 (2015)
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