Universality of the tunable-barrier electron pump at the part-per-million level

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***Abstract* — We summarize the results of precision measurement campaigns on semiconductor tunable-barrier electron pumps undertaken at NPL, over the last 5 years. We have investigated pumps of 3 different designs, fabricated in GaAs and silicon and operated on the 1-electron plateau at frequencies from 230 MHz to 1 GHz. For all measurements we find the pump current equal to $e\times f$ within the ≈1 ppm standard uncertainty of the current measurement. This accumulated data strongly suggests that accurate quantized operation of the tunable-barrier pump is a universal property, insensitive to the detailed design of the device. The data includes previously unpublished results.**

***Index Terms* — Electron pump, current standard, small current, primary electrical standard.**

I. INTRODUCTION

Clock-controlled transfer of single electrons in a nano-structured device is a direct and conceptually simple method of generating a primary reference current. Precision measurements on semiconductor tunable-barrier pumps [1]-[3] have demonstrated current quantisation accuracy at the level of 1 µA/A or better, and these devices are currently the focus of research efforts at many institutes worldwide.

While the operation of the tunable-barrier pump is believed to be described by universal physics [4], nano-fabrication technology provides a range of materials and methods for realizing the electron pump in practice. If the electron pump is to be adopted as a primary standard of current, it is necessary to show that accurate operation of the pump is indeed a universal property of the underlying physics, and not specific to one device design or material.

II. ELECTRON PUMP DEVICES

We report 6 high-accuracy measurements on 3 different tunable-barrier electron pump designs, which are denoted by the institute leading the work on each design: ‘NPL’, ‘KRISS’ and ‘NTT’. The NPL [1] and KRISS [2] samples are both fabricated using a Gallium Arsenide (GaAs) heterostructure, in which a 2-dimensional electron gas is formed below the sample surface. In contrast, the NTT pump [5] uses a silicon MOSFET architecture in which the electron density is controlled by a global top gate fabricated on top of the barrier gates. The NPL and KRISS pumps differ as follows: in the KRISS sample, confinement of the electrons is achieved solely through the use of electrostatic surface gates [2], whereas the NPL pump additionally uses a wet-chemical etching step to define a 2 µm-wide conducting channel prior to the patterning of surface gates [1].

The 6 measurements, in chronological order, were as follows:

1. NPL GaAs pump at 300 mK, result reported in [1].
2. KRISS GaAs pump at 300 mK, result reported in [2].
3. NPL GaAs pump at 300 mK, unpublished measurement on a different sample to that of ref. [1].
4. KRISS GaAs pump, a different sample to measurement 2, at the higher temperature of 1.3 K, paper in preparation.
5. Repeat of measurement 4 using the ultrastable low noise current amplifier (ULCA) [6] to measure the pump current.
6. NTT silicon pump, paper in preparation.

The pumps were cooled in a helium-3 cryostat with base temperature 300 mK, although for some of the measurements the helium-3 was not condensed, resulting in an elevated temperature ≈1.3 K. For all measurements, the pump gate voltages were tuned to the 1-electron plateau and the RF gate was driven at a frequency f. The current I_P was measured, and

978-1-4673-9134-4/16/$31.00

we define the deviation of I_P from its expected quantized value as $\Delta I_\mathrm{P} = (I_\mathrm{P}-ef)/ef$, where e is the electron charge.

III. CURRENT MEASUREMENT TECHNIQUES

All measurements apart from no. 5 were made using the NPL current measurement system, which has already been described in detail in ref. [1]. The unknown electron pump current I_P is traceable to a 1 GΩ resistor, and a voltage measured by a precision DVM calibrated directly against a Josephson array. A typical type A uncertainty for a 15 hour measurement of I_P=150 pA is ≈0.2 µA/A. The overall uncertainty in measuring I_P is ≈1 µA/A, dominated by the 0.8 µΩ/Ω type B uncertainty in the 1 GΩ resistor calibration (all reported uncertainties are standard 1σ uncertainties). In principle, a lower overall uncertainty for $I_\mathrm{P} \geq 200$ pA could be achieved using a 100 MΩ resistor [7], but this has not yet been used due to inadequate short-term stability of available thick-film resistance standards [8].

Measurement number 5 was made using an (ULCA) [6] calibrated at PTB. This device has demonstrated a trans-resistance gain stability of $\approx 10^{-7}$ over time-scales of several weeks [6], and a transport stability of better than 10^{-6} in an inter-laboratory comparison [8]. Unfortunately, a short measurement time meant that the uncertainty of measurement 5 was dominated by the type A component, and the low total uncertainty available using the ULCA [3] was not realized.

IV. RESULTS

In Fig. 1 we plot ΔI_P for measurements 1-6 in chronological order. For all measurements apart from nos. 3 and 5, the value plotted was an average of measurements over a range of tuning parameters for which I_P was invariant in the tuning parameter (a ‘flat plateau’). For measurements 3 and 5, the value plotted was obtained from a single measurement at one set of values of the tuning parameters.

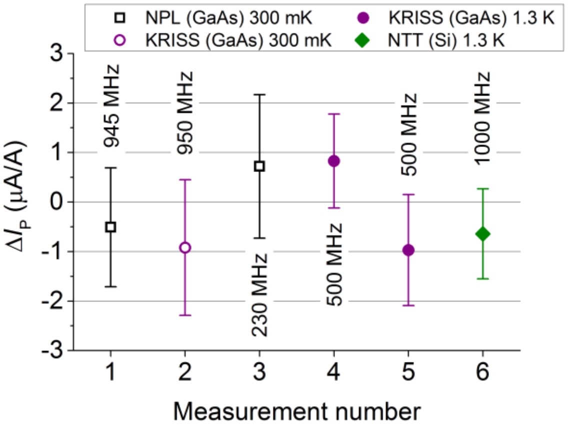

Figure 1. Summary of pump current for 6 precision measurements ordered chronologically. The pumping frequency is indicated next to each data point. Open (closed) points denote a temperature of 0.3 (1.3) K. Error bars show the total uncertainty.

All pumps demonstrated accurate quantization within the measurement uncertainty. We make two further observations: Firstly, the optimal gate voltage tuning generally could not be predicted solely by fitting to low resolution measurements as was done in [1]. Secondly, for all pumps, the quantization deteriorated dramatically above some critical frequency. The reported measurements were made at the highest frequency for which flat plateaus were observed over a reasonable range of gate tuning parameters.

V. CONCLUSION

We find that current quantization at the 1 µA/A level is a robust property of optimally tuned semiconductor tunable-barrier pumps operated at $f \leq 1$ GHz.

ACKNOWLEDGEMENT

This research was supported by the UK department for Business, innovation and Skills, and within the Joint Research Project “Quantum Ampere” JRP SIB07 within the European Metrology Research Programme (EMRP). The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

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