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Study of Quantisation Accuracy Breakdown due to High Temperature and High Frequency in a Silicon Single-Electron Pump

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Abstract

Solid state based single-electron pumps have been shown to produce a highly accurate current with part-per-million (ppm) accuracy [1,2], making them promising candidates to redefine the unit of current, the Ampere [3]. However, there has been universally observed degradation in the current accuracy with both increasing frequency and increasing temperature [4-7], which is not well understood. Here, we present detailed studies of such breakdown in the case of a silicon based single-electron pump, and find evidence that this breakdown is attributable to non-adiabatic excitation.

1. Introduction

There is a drive to redefine the Ampere using quantum standards. One candidate method is to count the output of a single-electron pump, a device which gives a quantised number of electrons in a known time. This would make the definition of the current standard not only of greater accuracy using quantum standards, but easier to realise. There has been much success in demonstrating this concept in many semiconductor materials [1,2], but there has been no demonstration of the 10^{-8} accuracy required to redefine the unit of current. Hence, understanding the operation of an electron pump and the processes that cause it to lose accuracy of quantisation are of high importance. In this paper, we explore the breakdown in accuracy with high temperature and high frequency, and in particular we explore the roles of a decrease in charging energy [8] and non-adiabatic excitations [9]. These mechanisms inhibit the measurement of high currents, making this current standard difficult to realise and measure.

2. Experimental details

Fig. 1(a) shows a sketch of our silicon single-electron pump and the electrical connections made. A conducting channel is defined in a Si nanowire of width (after oxidation) ~10 nm (light grey). Polycrystalline Si gates, separated by 70 nm, are formed to span the wire (orange). When energised, these form potential barriers in the channel. We denote the left barrier the *entrance* barrier, and the right the *exit* barrier. The region between the barriers defines a quantum dot (QD, dark circle). We apply a sinusoidal ac signal to the entrance barrier, V_{ent}^{AC}, with a dc offset such that at the low part of the cycle, electrons can populate the QD from the source lead, are then isolated in the QD, and finally pumped over the exit barrier, as the QD energy rises with the ac drive. This produces a pumped current $I = nef$, with n the number of electrons confined to the QD, e the elementary charge, and f the ac drive frequency. Measurements are performed in a dilution refrigerator and zero magnetic field.

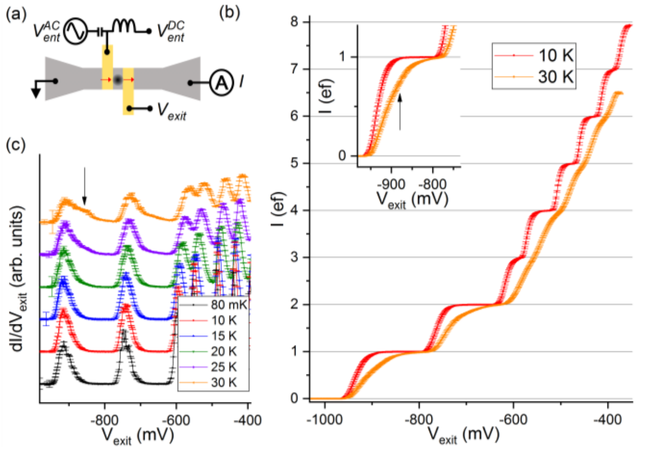

Figure 1. (a) Schematic of the electron pump and electrical connections. A conducting channel (light grey) defines a Si nanowire of ~10 nm width. This is spanned by Si gates, which on application of potential, confine electrons to the quantum dot (QD) (black circle). The ac drive loads and ejects electrons from the QD, producing a quantised current, in the direction indicated by red arrows. (b) Breakdown in quantisation accuracy at 100 MHz is clearly seen as temperature is increased. Inset: magnified view around the $n = 1$ plateau. (c) On examination of the derivative $\mathrm{d}I/\mathrm{d}V_{exit}$, we see evidence of excitation (arrow) which degrades the plateau, and similarly so for higher plateaus.

As the QD energy is lowered, we can pump more electrons per cycle. This gives the step-like trace of Fig. 1(b). The red trace, taken at 10 K, produces well defined plateaus up to $n = 8$. However, if we increase the sample temperature, there is a clear degradation of the plateau quality (orange trace, 30 K). The mechanism for this degradation could be expected to be from the increased thermal energy of the system, but the exact mechanism is unknown and this is what we study in detail here. The inset shows a close-up of the $n = 1$ plateau, clearly showing the reduction of the exit barrier region in which accurate pumping can be achieved.

Fig. 1(c) shows the derivative $\mathrm{d}I/\mathrm{d}V_{exit}$ with increasing temperature (vertically offset for clarity) at 100 MHz, from the base temperature of 80 mK to 30 K. The distributions are asymmetric, implying an out-of-equilibrium regime during isolation (the decay cascade model [10]). At the higher temperatures, a peak broadening (highlighted by the arrow) clearly occurs. In this case, electrons are loaded into

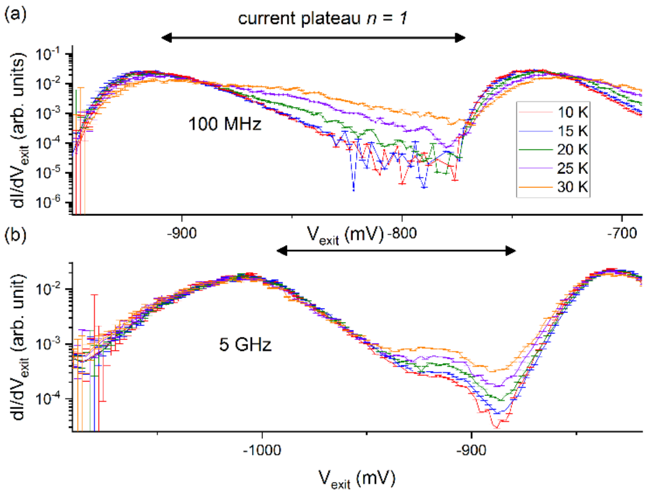

Figure 2. The effect of frequency on non-adiabatic excitation causing degradation of the current plateau (labelled). In the low frequency case (a), the excitation is strongly temperature dependent, implying thermally driven backtunnelling. In the high frequency case (b), there is a clearer separate distribution, present even at low temperatures, which is evidence for non-adiabatic excitation.

the QD and backtunnel, due to an increased thermal activation enhancing coupling to the source lead (because the entrance barrier is rising and so relatively low), reducing I. (Note that in Figs. 1(c), 2, 3, we have added a horizontal offset to some traces to align the maxima in the principal distribution. This is because the onset of the current I (Fig. 1(b)) change due to impurity traps and cross-coupling between the gates).

In Fig. 2, we examine this effect at higher frequency. In Fig. 2(a), we plot $\mathrm{d}I/\mathrm{d}V_{\mathrm{exit}}$ at 100 MHz, and in Fig. 2(b) at 5 GHz. In the ideal case, the distribution should fall to zero on the plateau (the region highlighted in each case by the arrow). Here, in both cases, there is some decrease in I ($\mathrm{d}I/\mathrm{d}V_{\mathrm{exit}} > 0$) due to excitation. In the low-frequency case, we observe strong temperature dependence, suggesting thermally driven backtunnelling. However, at high frequency, we note there is a distinct distribution on the plateau, and it is present at the lower temperatures. We attribute this effect as evidence of non-adiabatic excitation [9], which refers to the promotion of an electron confined to the QD to an excited state due to the rapid change of the QD potential. It is understood that conventionally, and in the most accurate pumping case, only the QD ground state is occupied (i.e. an adiabatic transfer through the QD). The temperature dependence of the decrease in current on the plateau at 5 GHz also indicates that the thermal energy alone can induce excitation (and this will also happen in the 100 MHz case to some extent).

It is also important to note that at 5 GHz the principal distribution attributable to the riser between the n = 0 and 1 plateaus is largely unaffected by temperature, suggesting that thermal activation is not important during the isolation process. This may suggest the timescale of the ac drive waveform raises the entrance barrier faster than thermal equilibration can take place.

Finally, in Fig. 3, we compare the distributions as previously studied at 10 K as a function of frequency. We observe a clear broadening of the rising edge with increased frequency.

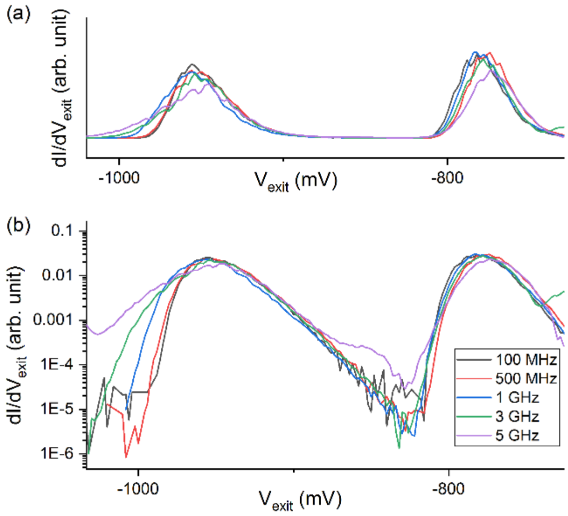

Figure 3. Frequency dependence in the distribution $\mathrm{d}I/\mathrm{d}V_{\mathrm{exit}}$. In both the linear plot (a) and the logarithmic plot (b), we can see clear dependence on the distribution width with frequency. Curves measured at 10 K.

We suggest this is due to an ac-induced local heating, which begins to make the distribution symmetric as thermal equilibrium is reached towards loading.

3. Conclusions

We have investigated the mechanisms by which single electron pumps, which operate as highly accurate quantised current sources at low frequency and low temperature, lose accuracy with increasing frequency and temperature. We find evidence to suggest this is due to an increased back-tunneling rate to the source lead. Both high temperature and high frequency contribute to the increased probability of backtunnelling to the source, but the phenomena is more strongly dependent on the ac drive frequency because this creates non-adiabatic excitation, likely because it changes the rate of change of QD potential (and perhaps position), whereas temperature mostly only increases the thermal activation of the QD levels. However, we also see evidence that the excitation can be induced by high temperature alone. Our work is likely to contribute to the better understanding of the electron pump mechanism of operation, which can allow better design so they can be used as a metrological standard.

References

[1] G. Yamahata et al., Appl. Phys. Lett. **109**, 013101 (2016).
[2] S. P. Giblin et al., Nature Commun. **3**, 930 (2012).
[3] J. P. Pekola et al., Rev. Mod. Phys. **85**, 1421 (2013).
[4] G. Yamahata et al., Phys. Rev. B **89**, 165302 (2014).
[5] K. W. Chan et al., Appl. Phys. Lett. **98**, 212103 (2011).
[6] J. D. Fletcher et al., Phys. Rev. B **86**, 155311 (2012).
[7] M. Seo et al, Phys. Rev. B **90**, 085307 (2014).
[8] G. Yamahata et al., Appl. Phys. Lett. **106**, 023112 (2015).
[9] M. Kataoka et al., Phys. Rev. Lett. **106**, 126801 (2011).
[10] V. Kashcheyevs and B. Kaestner, Phys. Rev. Lett. **104**, 186805 (2010).