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Performance of Silicon Based bi-directional Electron Pumps Consisting of Two Coulomb Blockade Devices

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1. Introduction

Recently silicon based Coulomb blockade (CB) devices have attracted much attention due to their CMOS compatibility. Bi-directional electron pumps consisting of two CB devices have been investigated with particular emphasis towards logic applications, reducing the power consumption as one of the limiting factors for the development of integrated circuits.[1,2] In this abstract we discuss the limits of the silicon based bi-directional electron pump presented so far.[3]

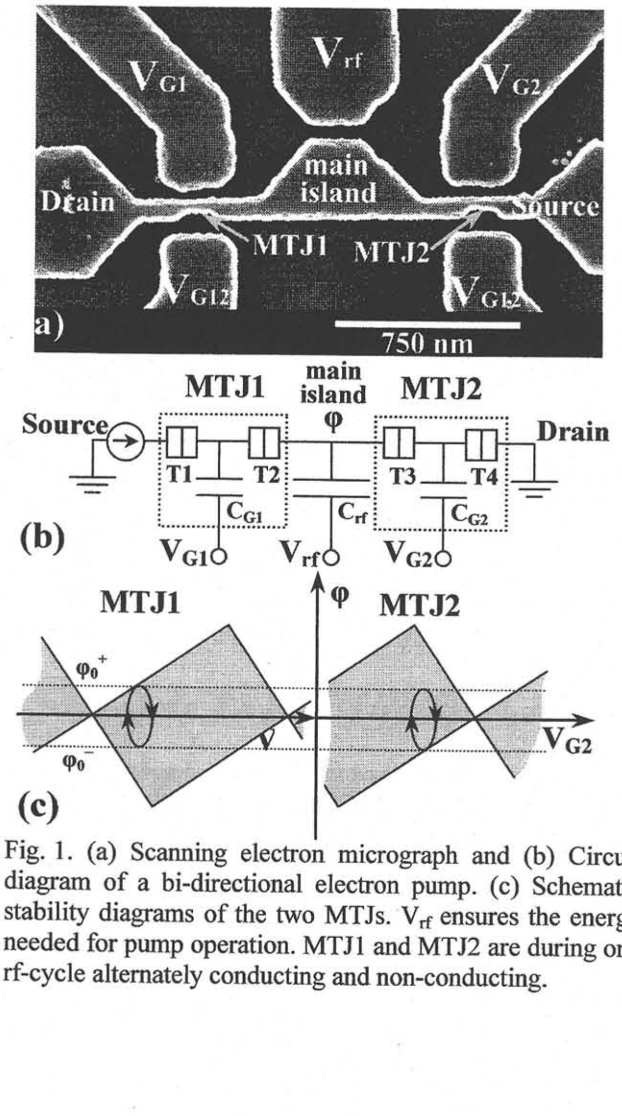

Fig. 1. (a) Scanning electron micrograph and (b) Circuit diagram of a bi-directional electron pump. (c) Schematic stability diagrams of the two MTJs. V_{rf} ensures the energy needed for pump operation. MTJ1 and MTJ2 are during one rf-cycle alternately conducting and non-conducting.

2. Fabrication

The devices were made in silicon-on-insulator material, with a 40 nm thick 2×10^{19} cm^{-3} phosphorus doped Si layer on top of 400 nm SiO_2. The Si is capped by 20 nm SiO_2. The multiple tunnel junction (MTJ) CB devices were defined by electron beam lithography using an Al mask for lift-off and subsequent reactive ion etching (RIE). After wet-chemical removal of the Al, the chip was oxidised for 5 min at 1000 °C to reduce the width of the wires from 35 nm to about 25 nm. Figure 1(a) shows the circuit at this stage.

2. Pump operation

The pump consists of two MTJs separated by a macroscopic island to which a clocking signal V_{rf} is applied [Fig. 1(b)]. The characteristics of MTJs can be described by the CB theory. V_{rf} causes φ to oscillate, making the two MTJs alternately conducting and non-conducting as indicated by the loops in fig. 1(c) Thus electron packets are shifted through the circuit.

3. Electrical Characteristics and Discussion

All measurements were carried out at 4.2 K with standard equipment. Figure 2 shows the pump current characteristic as a function of the two gate voltages V_{G1} and V_{G2}. The periodicity of the current peaks is determined by the CB oscillations. The positions of the current peaks as a function of the common gate V_{G12} stay stable for different frequencies. However, they shift and broaden with increasing amplitude, because with increasing φ the CB is overcome for a larger gate voltage regime. Thus the zero current plateaux between the two peaks which are well observable for a amplitude of 5 mV almost disappear at 45 mV. The peak height of the current as a function of frequency is ideally linear. However, if

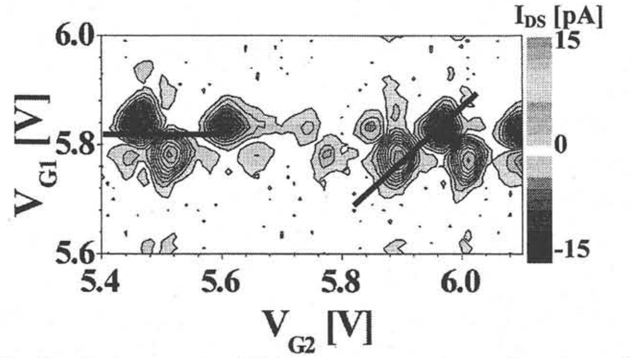

Fig. 2. Contour plot of the pump current as a function of V_{G1} and V_{G2}, for a frequency of 3 MHz and a 200 mV clock amplitude.

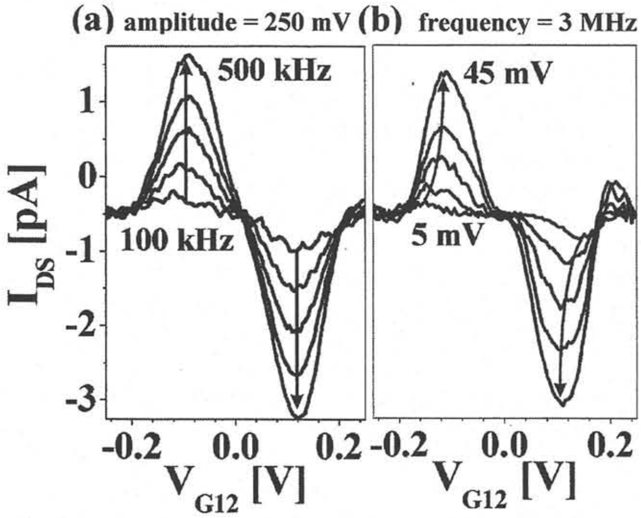

Fig. 3. Pump current as a function of (a) frequency and (b) clocking amplitude. The measurement was taken along the diagonal line in fig 2.

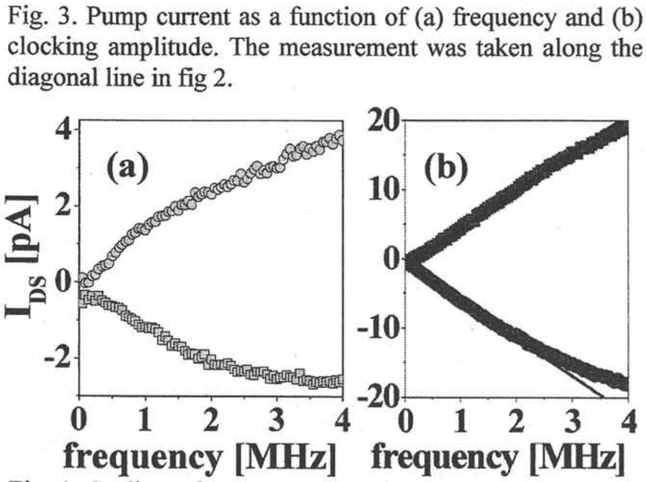

Fig. 4. Scaling of two current peak pairs as a function of frequency. The measurement were taken as a function of (a) V_{G2} and (b) V_{G12} corresponding to the horizontal and vertical line in fig. 2.

the frequency is below

$$f_{min} = (C_{rf}R_T)^{-1}exp[-e^2/C_{rf}kT],$$

the pump performance suffers from loss of electrons caused by thermally activated tunnelling. For frequencies above

$$f_{max} = e/(4V_0 R_T C_{rf}^2)$$

on the other hand, the island potential changes rapidly so that the MTJ through which the tunnelling should occur is non-conducting before the energetically favourable tunnel event takes place. C is the main island capacitance (stray capacitances are neglected), R_T the tunnel resistance of the tunnel junctions and V_0 the clocking amplitude. The non-linearities of the graphs in fig. 4 can be explained by these phenomena. The number of electrons transferred per cycle decays for frequencies above 2 MHz in both measurements. Thermally activated loss of electrons can be only observed in fig. 4(a) for frequencies below 400 kHz. The resistance of the circuit was in the order of 100 MΩ. Therefore its reduction down to 1 MΩ would increase the frequency window up to 40 < f < 200 MHz. If further miniaturisation of the device, in order to minimise C_{rf} is desired, cross-coupling phenomena from the clocking signal towards both MTJs might become important and needs to be taken into account.

4. Conclusion

The frequency and amplitude modulation of a bi-directional electron pump was compared and peak broadening for increasing clocking amplitude observed. The non-linear frequency dependences of the current peaks were explained by thermal loss of electrons at low frequencies and the lack of transitions at high frequencies. Further optimisation of the device geometry and the tunnel barriers in particular would improve performance.

Acknowledgments

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