A 7-JUNCTION ELECTRON PUMP: DESIGN AND OPERATION

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Abstract

We report progress in the development of a 7-junction electron pump for use in a new capacitance standard. Cross capacitance in the pump has been reduced with a new geometry of islands and gates. Stray capacitance and charge noise have been reduced by using a quartz substrate. With these and other improvements the pump has become a relatively easy-to-operate cryoelectronic device.

Introduction

The electron pump uses the Coulomb blockade of electron tunneling to control the flow of electrons along a chain of metal islands separated by ultrasmall tunnel junctions [1]. By applying a sequence of voltages to gate leads near each island, the blockade can be manipulated and a single electron can be passed along the chain. With the pump as an electron counter, a capacitance standard can be made by pumping a known number of electrons onto a capacitor and measuring the voltage that develops across the capacitor [2]. NIST is currently working to develop such a standard, which will likely be the first practical application of single electron tunneling (SET). A long-term metrology goal is to combine the new capacitance standard with the calculable capacitor and the Josephson voltage standard to achieve a new measurement of the fine structure constant [2].

A useful capacitance standard requires a pump with an error smaller than about 10 ppb. In previous work at NIST, a 5-junction pump has been operated with an error of about 500 ppb [3]. Our current understanding of SET error processes indicates that a 7-junction pump should achieve the desired error level, so we are working to build such a device and test its accuracy. Other components needed for the capacitance standard are being developed simultaneously [4].

Improved Pump Design

We have made several refinements aimed at transforming electron counting from a novel laboratory phenomenon to a robust process that can be the basis for a new metrological standard. Most of the design considerations used for the pump can also be applied to other SET devices.

Cross Capacitance

The islands and gates of the electron pump are shown in Figure 1. When a voltage is applied to one gate, the island nearest that gate line is polarized with a charge, but significant polarization also occurs on neighboring islands. In order to achieve the desired sequence of island polarizations, this cross capacitance effect must be eliminated. We do this by electronically adding cancellation voltages of opposite polarity to each of the neighboring gate lines.

For the 5-junction pump (Figure 1a), the capacitance C_{nn} between each gate and the nearest neigbor island was about 40% of the direct gate-to-island capacitance C_g. The cancellation voltages had to be carefully optimized for each pump device *in situ*, which was a slow and tedious process requiring about an hour when done by a skilled operator. In the 7-junction pump (Figure 1b), the geometry has been changed to reduce C_{nn} to 20% of C_g. With this design, finding the optimum cancellation voltages is much less critical. The cancellation voltages can be accurately predicted from a two-dimensional calculation of the cross capacitance and very little *in situ* optimization is needed (see the discussion of Figure 3 below).

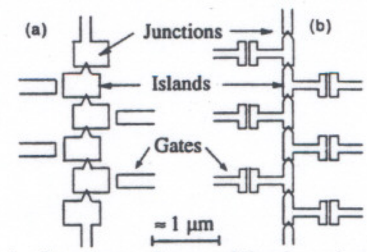

Figure 1: Geometry of pump islands and gates. (a) 5-junction pump. (b) 7-junction pump. (The dual image from the double-angle evaporation is not shown for clarity). The tunnel junctions are located at the sharp tip at the top of each island.

Stray Capacitance

In order to avoid unwanted tunneling events, the total capacitance of each island in the pump, $C_{tot} = C_j + C_g + C_{stray}$, must be small [1]. Since the geometry is constrained by the need to minimize cross capacitance, C_{stray} can be adjusted primarily by changing the dielectric constant of the substrate. Previous work on the 5-junction pump used a sapphire substrate with $\varepsilon \approx 10$. With the geometry of Figure 1a, $C_{stray} \approx 0.22$ fF. For the 7-junction pump we have used fused quartz with $\varepsilon = 3.75$. With the geometry in Figure 1b, $C_{stray} \approx 0.07$ fF. This reduction in C_{stray} allows us to obtain the same C_{tot} as before with a larger C_j, which means the junctions can be larger and easier to fabricate.

Other Improvements

• We have built a custom header/socket assembly using Au-plated contact pins epoxied into holes in a Cu base and Au-plated sockets soldered into a printed circuit board. The chip is attached to the header with grease and Al wire bonds are used to make electrical contact. This system allows us to measure pump devices many times over long periods and to easily transfer devices between laboratories. It will facilitate the development of the new capacitance standard which will be developed jointly by NIST researchers in Boulder and in Gaithersburg.

• A scanning force microscope has been used to obtain images of the actual devices before measurement without any apparent damage to the ultrasmall tunnel junctions. This allows us to measure the dimensions of each junction in a device and provides accurate input for our capacitance calculations. It also allows us to avoid the time and expense of cooling down devices with fatal submicrometer flaws that cannot be detected with an optical microscope.

Experimental Results

The circuit used to study the electron pump is shown in Figure 2. The pump is connected to an external island

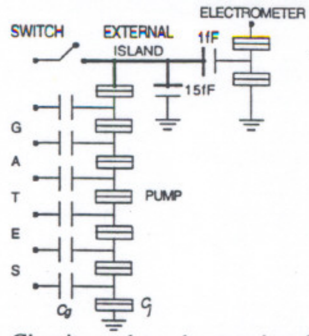

Figure 2: Circuit used to characterize the electron pump and to measure errors. All components except the mechanical switch are fabricated on a single chip. The switch and the chip are enclosed in a sealed copper box. The gate lines have attenuators and the other lines have RF and microwave filters to reduce the high frequency noise entering the box.

shown with heavier lines. The electrometer is an SET device that can detect a charge of much less than e at its input capacitor [1]. With an input capacitance of about 1 fF and an external island capacitance of about 15 fF, the electrometer can easily detect a change in the island charge of e. The mechanical switch is a magnetically controlled arm with a needle which contacts a metallic pad that is part of the external island. With the switch closed, the current-voltage curve of the pump and the gain of the electrometer can be measured. With the switch open, the electrometer can be used to detect intentionally pumped electrons or errors.

Cross Capacitance Cancellation

The voltage across the pump V_p at constant bias current is fundamentally periodic in the charge on any island with period e. If each gate polarizes only one island, V_p is then a periodic function of the voltage V_g on any gate. Figure 3 shows V_p *vs.* V_g without (left side) and with (right side) cross capacitance cancellation. This result clearly shows we have obtained the desired cancellation of the polarization on neighboring islands so that each gate polarizes only the nearest island. Achieving the periodic behavior on the right is critical for pumping electrons at the lowest error level.

Charge Noise

The noise of the SET electrometer is dominated by the random motion of charges in the substrate which couple capacitively to the electrometer input. This charge noise limits the sensitivity of our error measurements and will be an important limit to the accuracy of the SET capacitance standard. Preliminary measurements of a device made on a fused quartz substrate show an input charge noise at 10 Hz

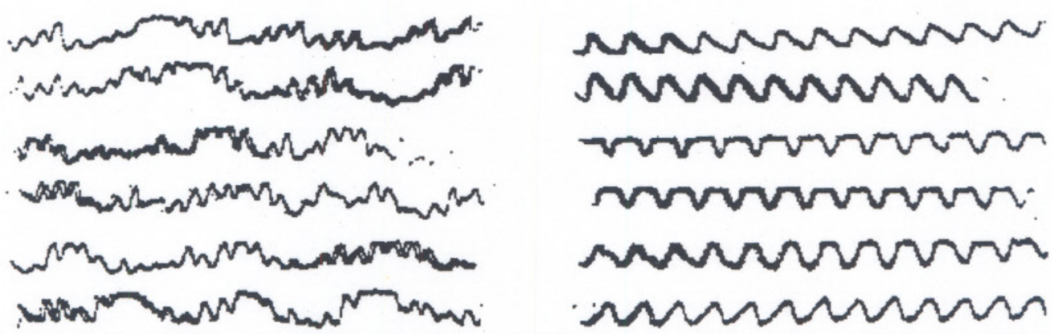

Figure 3: Cancellation of the cross capacitance. Each trace is V_p at constant bias current *vs.* V_g for one of the six gates. Left: No cancellation. Right: Cancellation voltages predicted from capacitance calculation. The periodic oscillations on the right have a period of about 1.5 mV and a height of about 30 μV (all traces have the same scale).

of 10^{-3} $e/\sqrt{\text{Hz}}$. When scaled by the total capacitance of the island defined by the electrometer junctions and input capacitor, this is about half the noise shown by previous devices made at NIST on sapphire, silicon, or oxidized silicon substrates.

Conclusion

With the improvements described above, we have made a 7-junction pump that is easier to operate than the 5-junction pump, despite the increased complexity of additional junctions and gates. Minor technical problems have prevented us from operating the pump under optimal conditions to date, but preliminary results indicate an error level less than 100 ppb. With further work we expect the 7-junction pump to achieve much greater accuracy.

Acknowledgements

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References

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