# Counting Electrons One by One—Overview of a Joint European Research Project

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***Abstract*—The European COUNT project exploits two complementary single electron tunneling devices for use in electrical current metrology: a single electron pump as a current source and a single electron counter as a current meter. An electron pump has been developed with on-chip resistors in order to suppress cotunneling. The intended accuracy is 1 ppm for a current of a few picoampere. Apart from being a quantum current standard, the electron pump could also be the basis of a capacitance standard. A coaxial tunable cryogenic capacitor of 1 picofarad has been developed for this purpose. A passive electron counter based on a single electron transistor embedded in a resonant tank circuit has been further investigated and developed in order to reach both high sensitivity and high counting speed. The intended accuracy is 10 ppm for a current of a few picoampere.**

***Index Terms*—Capacitance, charge transfer, current measurement, single electron counter, single electron pump, tunnel transistor.**

## I. Introduction

OVER a decade ago, scientists managed to control the movement of single electrons through devices with characteristic dimensions in the nanometer region. It was readily recognized that this so-called single electron tunneling (SET) effect could be the basis for a quantum standard of electrical current. Consequently, several major national metrology institutes (NMIs) have started research programs aiming at the realization of such a standard. Several promising SET techniques have been investigated since then [1].

From a fundamental point of view, a quantum standard for current is of great importance, since the ampere is one of the seven SI base units. The SET current standard closes the so-called quantum triangle, relating voltage, current, and frequency by quantum effects.

SET effects are visible in systems which contain a small metallic island, weakly coupled (e.g., through tunnel junctions) to an external circuit. When the island capacitance $C_\Sigma$ is sufficiently small, the presence of an extra electron on the island can easily be detected. This effect is most clearly observable when the charging energy $e^2/2C_\Sigma$ is the dominant energy in the system because it exceeds the energy of the electrons associated with the applied voltage $eV$ and their thermal energy $kT$. For metallic structures with characteristic dimensions smaller than 100 nm, this requires operation at temperatures below 50 mK.

By attaching a capacitive gate coupling to the island, the island charge can be manipulated. The most familiar SET structure is the single electron transistor, which has two tunnel junctions and one gate capacitance. Two more complicated devices, an electron pump and an electron counter, will be discussed below; they are the focus of the European COUNT project.

## II. SET Current Source: The R-Pump

The electron pump has $n$ junctions $(n > 2)$ and $n-1$ gates which are supplied with an ac signal of frequency $f$. When the amplitude and phase of the $n-1$ signals is correct, the current equals $I = e \times f$. For small $n$, the dominant error in this transport rate is due to co-tunneling, which is simultaneous tunneling of electrons through several islands. Co-tunneling can be reduced to acceptable levels by increasing $n$ to 7 [2]. However, the resulting six ac control signals demand a complex tuning procedure to cancel cross-capacitances between islands.

An alternative technique to reducing co-tunneling in small $n$ pumps has been developed at PTB as part of the COUNT project [3]. On-chip resistive Cr-microstrips of typically 50 kΩ are placed in series with the pump (see Fig. 1). These resistors cause higher (as compared to a device without resistors) energy dissipation of the tunneling electrons, which suppresses undesired higher order quantum mechanical effects such as co-tunneling more strongly than the desired tunneling events.

The first experiments on a three-junction R-pump show that it is superior to those of its analog without on-chip resistors. In the pumping regime, the current steps on the $I$–$V$ curve exhibit an evaluated differential resistance $> 50$ GΩ for a sample with room temperature resistance of 400 kΩ, which indicates

Manuscript received June 17, 2002; revised November 8, 2002. This work was supported by the EU as part of the Framework Programme 5 under Contract G6RD-CT 1999-00046.

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Digital Object Identifier 10.1109/TIM.2003.810736

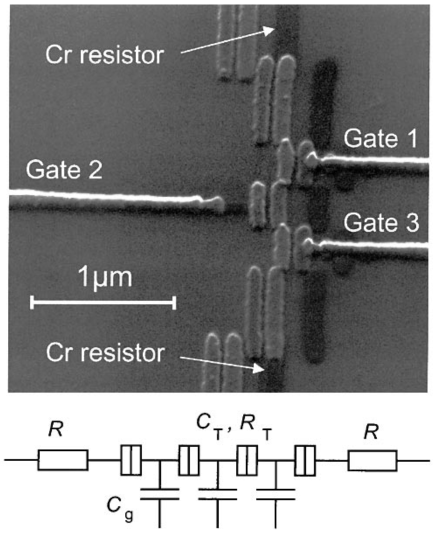


Fig. 1. SEM-image and equivalent circuit of four-junction single electron pump with on-chip Cr resistors in series.

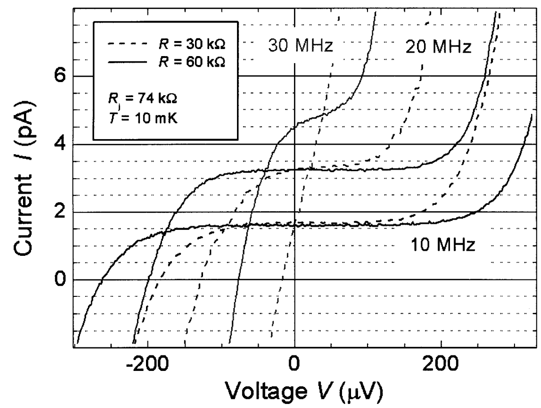


Fig. 2. Current steps for the R-pump with smaller junctions for different frequencies and series resistances $R$. For different $R$s, one can clearly observe the effect of resistors on the current step width.

a wide range of stable pump operation by the offset voltages. The accuracy of pumping was evaluated to be on the order of 100 ppm for a current of 1 pA, based on a practical uncertainty of a few microvolt in setting the bias voltage. The pumping accuracy in these experiments is probably mainly due to the increased temperature of 80 mK, which can be evaluated from the rounding of the $I$–$V$ curves while pumping. A more accurate way of determining the pumping accuracy is by measuring the leakage charge on a neighboring island while pumping one electron to and from the island, such that the average transport in time should be zero [2].

The results of the first tests were used for further design optimization. In particular, the junctions were reduced in size down to $20 \times 40$ nm$^2$, while maintaining low resistance. The estimated junction capacitances were below 150 aF. As an effect of these smaller tunnel junctions, an increased Coulomb blockade region and increased step size were observed, indicating better stability against error mechanisms. Due to the reduced RC-product, it was possible to observe well-pronounced pumping up to the frequencies $f \approx 30$ MHz (see Fig. 2). For different resistors (different configurations of Cr microresistors), one can clearly observe the remarkable effect of resistors on the current step width and, hence, on stability of the pumping regime.

The zero-temperature rate of co-tunneling in a three-junction R-pump has been calculated independently using both numerical and analytical approaches. For these calculations, realistic parameters (resistance and capacitance of the tunnel junctions, resistance of Cr-micro-strips) of our experimental R-pumps were considered. The results show that even at zero temperature the metrological accuracy of 10 ppb can be achieved only with the state-of-the-art three-junction R-pumps whose parameters approach the practical limits of the fabrication process [3]. On the other hand, our estimations made for a similar four-junction pump demonstrated improvement of the pumping accuracy by two or three orders of magnitude. The operating speed of the four-junction devices is expected to be similar to that of the three-junction devices, i.e., giving a dc current of several picoamperes. The intended accuracy is 1 ppm for a current of a few picoampere. If necessary five-junction devices will also be developed.

When an R-pump is connected to a high stability capacitor suitable for low-temperature applications (a so-called cryogenic capacitor) [4], it can be used to charge the capacitor with electrons one by one [5]. Measuring the resulting voltage across the capacitor, and transferring the value of the capacitor to room temperature capacitors results in a quantum capacitance standard in terms of e. As part of the COUNT project, new types of stable, reproducible cryogenic coaxial capacitors have been developed [6], [7]. The METAS design incorporates mechanisms to enable them to be tuned precisely to a nominal value of 1 pF [6]. The coaxial design results in excellent stability, since at first order small radial displacements of the electrodes relative to each other do not result in changes in capacitance. The capacitor was measured to be free from drift and stable in time to better than 1 ppm for several hours, both at room temperature and at cryogenic temperatures. The temperature dependence of the capacitor from 300 to 4 K has been investigated using an Andeen-Hagerling 2500-A capacitance bridge. Several temperature cycles were performed to establish the capacitor's temperature dependence. Knowledge of this temperature dependence enables us to adjust it at room temperature such that its value at low temperature will be within 100 ppm of 1 pF, enabling the most accurate types of ac bridge to be used to compare it with a room temperature standard.

## III. SET Current Meter: The RF-SET

A single electron counter consists of a long one-dimensiona (1-D) array of islands capacitively coupled to an SET transistor (see Fig. 3). When an electric current is forced through the array, electrons are transferred quasiregularly, enabling the SET transistor to sense the passage of the individual electrons that make up the electric current. Contrary to the case of the electron pump, where individual electrons are actively forced to move, the electron counter will passively detect passing electrons.

The method of electron counting relies on a detector that is not only able to detect the minute charge variations when electrons pass, but also to do this at a high speed. Conventional

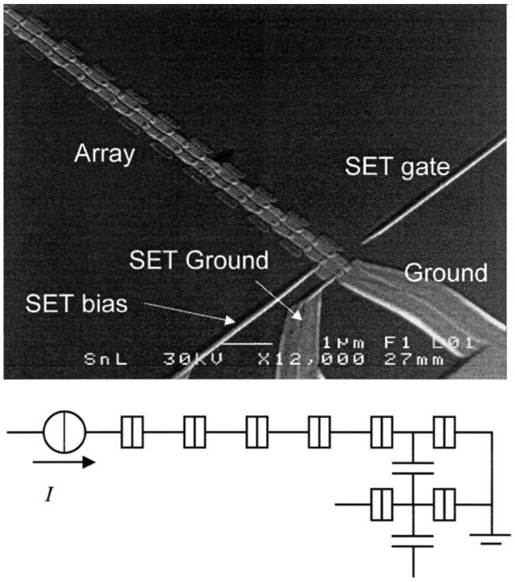


Fig. 3. SEM picture and schematic representation of a capacitively coupled electron counter.

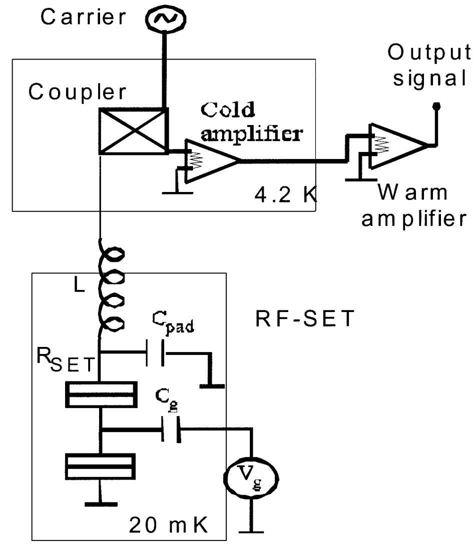


Fig. 4. Schematic representation of the RF-SET resonant circuit. The inductor is chosen such that it forms a resonant circuit with the parasitic capacitance, $C_{\rm pad}$, of the contact pad. By changing the gate voltage $V_g$ the resistance of the SET transistor is influenced.

SET-based electrometers are limited to operation speeds of typically 1 kHz, corresponding to a maximum current of 0.1 fA. Recently a single electron transistor has been developed that can be operated at radio frequencies (RF-SET) [8]. In the COUNT project, the RF-SET is optimized and adapted for accurate current measurements. The aim is to reach an accuracy of 10 ppm for currents up to a few picoampere.

In the RF-SET, the sensing SET transistor is integrated in a resonant circuit formed by an external inductor $L$ together with the parasitic capacitance $C_{\rm pad}$ of the bonding pad of the transistor (see Fig. 4). By changing the gate voltage, the differential resistance, $R_{\rm SET}$, of the sensing transistor is influenced: for some values, the transistor is blocked (i.e., $R_{\rm SET} \gg 1$ M$\Omega$), while for others it is open (i.e., $R_{\rm SET} \approx 50$ k$\Omega$). The resulting rapidly changing resistance value $R_{\rm SET}$ can be observed by measuring the reflection of irradiated power. In the case of an electron counter, passing electrons modulate the gate voltage. The counting speed of the device is limited by the quality factor $Q$ of the resonant circuit, which should not be too high in order to be sensitive to rapidly changing signals.

In reflection experiments, the SET impedance $R_{\rm SET}$ should match the impedance of the microwave transmission line. While the parasitic capacitance $C_{\rm pad} \approx 0.3$ pF is given, the external inductance was chosen to be $L \approx 750$ nH for a carrier frequency $f_0 \approx 330$ MHz. A setup with smaller inductance for use at higher frequency is also under development, in order to obtain higher counting speed. A microwave fixture in which the tank circuit inductor and the transmission line are integrated on a single substrate has been developed, fabricated, and tested for routine characterization of the RF-SET.

In order to test the working principle of the RF-SET, instead of a current through a 1-D array, a 2-MHz gate signal is applied with an amplitude of about $C_g V_g \approx 0.0095$ e$_{\rm RMS}$ [9]. As can be seen in Fig. 5, apart from the frequency of the irradiated power, the reflected power shows two side bands. These side-

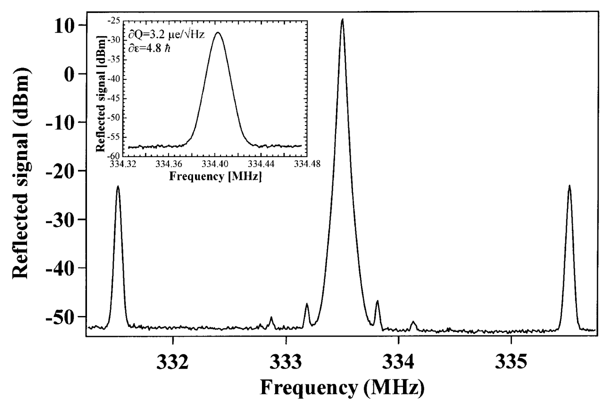


Fig. 5. Reflected power versus the carrier frequency. The carrier is amplitude modulated by the SET, generating two side bands, for a signal at gate of 0.038 e$_{\rm RMS}$ and 2 MHz. The inset shows the reflected signal as a function of the frequency for one of the sidebands, with a gate signal corresponding to 0.0095 e$_{\rm RMS}$ and 1MHz. From the measured data, we can deduce a charge sensitivity of 3.2 $\mu$e/$\sqrt{\rm Hz}$. The SET was in superconducting state and the drain-source bias was 0.856 mV.

bands differ an amount $f$ in frequency compared to the carrier, indicating that it has detected a fictitious current $I = e \times f$.

The signal-to-noise ratio determines the sensitivity of the device. At low frequency 1/f-noise is the main factor, while at frequencies in the MHz range the white noise of the amplifiers and other components dominates. At present, the charge sensitivity $\delta q = C_g \delta V$ of the best sample so far is 3.2 $\mu$e/$\sqrt{\rm Hz}$, corresponding to an energy sensitivity $\delta\epsilon = (\delta q)^2/2C_\Sigma = 4.8\ \bar{h}$ [9]. Note that this sensitivity has a fundamental lower limit of $\bar{h}$, which is determined by shot noise.

Although the detector itself needs some optimization, the emphasis with respect to the development of the electron counter will be on adapting the RF-SET for current measurement operation. The RF-SET is a multipurpose device that will not only be given its first application in metrology, it is also useful as a diagnostic tool for devices (sensors, logic or memory elements) that operate on the basis of single electrons.

## IV. Summary and Conclusion

The European project COUNT aims for the realization of a quantum standard for electrical current. The focus is on the improvement of two complementary SET devices: an electron pump (R-pump) in order to generate currents and an electron counter (RF-SET) in order to measure currents up to a few picoamperes.

The first measurements carried out at several laboratories of the COUNT consortium, both on R-pumps and on RF-SET devices, seem to be very promising. Optimization of device parameters and measurement techniques is necessary in order to reach the desired accuracy.

For more information and current progress of this project, visit www.count.nl.

## References


[1] K. Flensberg, A. A. Odintsov, F. Liefrink, and P. Teunissen, "Toward single-electron metrology," *Int. J. Modern Phys. B*, vol. 13, pp. 2651–2687, 1999.

[2] M. W. Keller, J. M. Martinis, N. M. Zimmerman, and A. H. Steinbach, "Accuracy of electron counting using a 7-junction electron pump," *Appl. Phys. Lett.*, vol. 69, pp. 1804–1806, 1996.

[3] S. V. Lotkhov, S. A. Bogoslovsky, A. B. Zorin, and J. Niemeyer, "Operation of a 3-junction single electron pump with on-chip resistors," *Appl. Phys. Lett.*, vol. 78, pp. 946–948, 2001.

[4] N. M. Zimmerman, "Capacitors with very low loss: Cryogenic vacuum-gap capacitors," *IEEE Trans. Instrum. Meas.*, vol. 45, pp. 841–846, Oct. 1996.

[5] M. W. Keller, A. L. Eichenberger, J. M. Martinis, and N. M. Zimmerman, "A capacitance standard based on counting electrons," *Science*, vol. 285, pp. 1706–1709, 1999.

[6] F. Overney, B. Jeanneret, and M. Furlan, "A tunable vacuum-gap cryogenic coaxial capacitor," *IEEE Trans. Instrum. Meas.*, vol. 49, pp. 1326–1330, Dec. 2000.

[7] G.-D. Willenberg and P. Warnecke, "Stable cryogenic vacuum capacitor for single-electron charging experiments," *IEEE Trans. Instrum. Meas.*, vol. 50, pp. 235–237, Apr. 2001.

[8] R. J. Schoelkopf, P. Walgren, A. A. Kozhevnikov, P. Delsing, and D. E. Prober, "The radio-frequency single-electron transistor (RF-SET): A fast and ultrasensitive electrometer," *Science*, vol. 280, pp. 1238–1242, 1998.

[9] A. Aassime, D. Gunnarson, K. Bladh, R. S. Schoelkopf, and P. Delsing, "The radio-frequency single electron transistor: Toward the quantum limit," *Appl. Phys. Lett.*, vol. 79, pp. 4031–4033, 2001.


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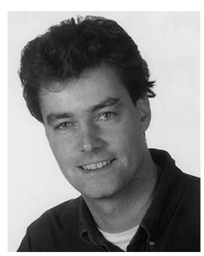

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