Current Measurement by Real-Time Counting of Single Charges

- Introduction, single electron counting
- Results
  - Counting of single electrons
  - Crossover from electron to Cooper-pair counting
- Summary

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Nature 434, 361 (2005)
LT 24 (2005), ISEC (2005)
Measuring current by counting single electrons

Normal current measurement
Measurement of a voltage drop across a resistor

Referenced to quantum Hall resistance and Josephson voltage

The COUNTer:
Counts the electrons one by one that are passing through a circuit

Can be coupled in parallel

\[ I = \frac{V}{R} \]

Suggestions for electron counters by Likharev, Visscher, Teunissen et al.
Coupling the array to the SET

As charge in the array approaches the SET the current in the SET is modulated.

Direct coupling gives full $e$ charge and thus better Signal to noise

Capacitive coupling, more linear
Eliminates back tunneling
The Radio-Frequency
Single Electron Transistor

Very high speed: 137 MHz
R. Schoelkopf, et al. Science (98)

Charge sensitivity: $\partial Q = 3.2 \mu e/\sqrt{Hz}$
Aassime et al., APL 79, 4031 (2001)

$R_{SET} = 44.1k\Omega$
$C_\Sigma = 370\ aF$
$C_g \approx 20aF$

$I$ (nA) vs. $V$ (mV) plot

Bias-Tee
Directional Coupler
Tank circuit
Cold Amplifier
Warm Amplifier
Mixer
RF-source
Output
SET-bias
Single Electron Transistor
RSET=44.1kΩ
CΣ=370 aF
Cg≈20aF

Per Delsing
Quantum Device Physics
Placing a single electron on one of the electrodes polarizes the array and gives rise to a “Charge soliton”

These charge solitons repel each other and thus line up in a 1D quasi Wigner lattice

Spatial correlation transfers to time correlation

Soliton size

\[ \Lambda = \sqrt{\frac{C}{C_0}} \]

Simulations

We expect to see a time signal at the output of the SET which has a frequency $f_{\text{SET}}=I/e$, i.e. SET-oscillations.

50 junctions
I= 250 fA
T=0

Capacitive coupling
The Single Electron Counter

Tripple angle evaporation, direct coupling

Array coupled directly to SET, i.e. R-SET configuration

Tri-angle evaporation

$R_{\text{SET}} = 30k\Omega$

$R_{\text{array}} = 940k\Omega/jcn$

Charge solitons line up as a train in the array
Current-Voltage Characteristics of the Array

- Sharp onset of current in the normal state
- Smooth onset in the superconducting state

$R_{jc}=940\,k\Omega$

$E_C \approx 2.2\,K$

$E_J \approx 6\,mK$

Counting in the SC-state gives a more stable current.

$B=475\,mT$

$B_c=650\,mT$
**Counting in Time and Frequency Domain**

Direct observation of the SET-oscillations

\[ f_{\text{SET}} = \frac{I}{e} \]

Time resolved counting of single electrons

- Ben-Jacob, Gefen, Phys. Lett. (1985)
- Averin, Likharev, JLTP (1986)
Comparing Current with Frequency

The red ridge corresponds to the peak in the frequency spectra.
Peak heights have been normalized.
White line is $f_{\text{SET}} = I/e$
5fA to 1pA
Comparing Room Temperature measurement with counter

- Counter
- Room temp am-meter
  Keithley Calibrator/source
The line width of the oscillations can be well fitted to a Lorentzian shape. The measured line width agrees very well with the simulated line width. At low current there is an additional broadening, probably due to uncertainty in the bias.
The capacitively coupled counter

Response is more linear, Signal to noise is not so good.
Crossover from electron to Cooper-pair counting

Power spectra for several different magnetic fields 200-500 mT

\[ Q_{\text{count}} = \frac{\text{Current}}{f_{\text{peak}}} \]

\[ I_{\text{bias}} = 200 \text{fA} \]

Single electron tunneling

Incoherent Cooper-pair tunneling

\[ \frac{E_J}{k_B} \approx 5 \text{ mK} \]

\[ T \approx 150 \text{ mK} \]

Duty, Bylander, Delsing in preparation
Crossover from electron to Cooper-pair counting

Whether electrons or Cooper-pairs tunnel in the array depends on the threshold voltage. When the voltage is higher than both thresholds, the rates become important.

The threshold voltages depend on magnetic field (and background charge)

When the voltage exceeds both injection thresholds, the tunneling probabilities will start to be important.

\[ \frac{\Gamma_e}{\Gamma_{2e}} = ? \]

The Tunnel probabilities depend on energy gap and (subgap-) resistance, and on background charges ….
Crossover from electron to Cooper-pair counting

\[ <n> = \frac{I}{ef} \]

Peak width \( \gamma/f_{\text{peak}} \)

1e both at low voltage and high field

1e peaks are more narrow
Upper and lower current limits

Minimum counting rate

At low currents only one electron is present in the array, spatial and thus temporal correlation is lost.

Current stability will smear the peak in the frequency domain.

Maximum counting rate

To maintain time correlation the current needs to be low, typically $I < 0.03 \, e/RC$.

Speed of the RF-SET, in our case ~10MHz.
Future directions

- Improving signal to noise, Squid amplifier
- Coherent versus incoherent 2e, Bloch oscillations
- Accuracy, how small currents can we measure
- Larger currents, parallel counters
- Looking at other systems, nanotubes, nanowires …
- Counting statistics, (linear detectors)…