Hybrid single-electron turnstile

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Metrological Quantum Triangle

Requirement: Current > 100 pA with accuracy $10^{-7} \ldots 10^{-8}$

Charge pumps: general principle

Cyclic operation (frequency $f$) of gates, $q_i = C_{gi}V_{gi}/e$, induces charge transport.

$I = ef$

H. Pothier et al., EPL 17, 249 (1992)
Single electron sources

Towards frequency-to-current conversion

Normal single-electron pump: \( I = e f \)

Geerligs et al. 1990
Keller et al. 1996
Lotkhov et al. 2000
High accuracy but still slow: \( I < 10 \text{ pA} \)

Semiconductor devices, travelling wave or quantum dots:

Shilton et al. 1996
Fujiwara et al. 2004
Blumenthal, Kaestner 2007
Fast, but need still improvement

Fully superconducting devices:

Several versions, see eg. Nguyen et al. 2007, non-adiabatic pump at NEC, phase slips
Fast, but still work to be done

Mechanical shuttles:

Konig, Weig et al. 2008
Adiabatic pumping of Cooper pairs

\[ H = -E_{J1} \cos\left(\frac{\varphi}{2} - \theta\right) - E_{J2} \cos\left(\frac{\varphi}{2} + \theta\right) + E_C (N - q)^2 \]

Tunable SSET: \( E_{J1}(\Phi_1), E_{J2}(\Phi_2), q \)
– two valves and one piston

\[ Q_P / (2e) \simeq 1 - 2 \frac{E_{J,\text{res}}}{E_J} \cos \varphi \]

Adiabatic transport of charge by supercurrent and pumping

\[ \langle \hat{I}_\ell \rangle = \langle m | \hat{I}_\ell | m \rangle + 2 \Re \langle m | \hat{I}_\ell | dm \rangle \]

usual supercurrent

\[ \langle m | \hat{I}_\ell | m \rangle \equiv I_{S,\ell} = \frac{\partial E_m}{\partial \varphi} \]

geometric contribution due to non-stationary control parameters

\[ Q_{\text{cycle}} \equiv \int \langle \hat{I}_\ell \rangle dt = \int I_{S,\ell} dt + Q_P \]

\[ \theta_{\text{Berry}} = i \int \langle m | dm \rangle \]

\[ Q_P = -2e \frac{\partial \theta_{\text{Berry}}}{\partial \varphi} \]

Measurement of Berry phase by coherent pumping

Hybrid single-electron turnstile (SINIS or NISIN)

One electron is transferred through the turnstile in each gate cycle: \( I = e f \).

Single electron transistor

Normal state SET

Hybrid SINIS SET
Stability diagrams

**Normal SET**

**Hybrid SET (SINIS or NISIN)**

Important qualitative difference: stability regions overlap in a hybrid SET unlike in a normal SET
Hybrid single-electron turnstile (SINIS or NISIN) – the first experiments
Multi-turnstile configuration

Each turnstile can be addressed individually in DC (IV measurements and background charge offset tuning)

Common AC drive for all the parallel turnstiles
Realization of the parallel device
Experiments on parallel turnstiles

**4 PARALLEL TURSTILES**

**10 PARALLEL TURSTILES**
Charge stability

10 turnstiles
Accuracy in the very first experiments
Thermal error rates

Probability (per cycle) of tunnelling in wrong direction is approximately

\[ \exp\left(-\frac{eV}{k_BT_N}\right) \]

Probability (per cycle) of tunnelling an extra electron in forward direction is approximately

\[ \exp\left(-\frac{2\Delta-eV}{k_BT_N}\right) \]

Optimum operation point is therefore at \( eV = \Delta \), where the error rate is

\[ \sim \exp\left(-\frac{\Delta}{k_BT_N}\right) \]

At 100 mK for aluminium (\( k_B T_N/\Delta = 0.04 \)), this error is \( << 10^{-8} \)

But: thermal errors grow with operation frequency, low \( T_N \) is very desirable!
Ultimate error rates – higher order processes

COTUNNELLING OF QUASIPARTICLES IN A SINIS STRUCTURE IS EFFICIENTLY SUPPRESSED

"Usual" NININ transistor

Threshold: $eV = 0$

SINIS transistor

Threshold: $eV = 2\Delta$
Andreev process and Cooper pair – electron cotunnelling

METROLOGICAL REQUIREMENTS ARE SATISFIED IN THEORY, BY USING 5 – 10 PARALLEL TURNSTILES

Leakage in NIS junctions

IMPROVED JUNCTIONS:

THE FIRST EXPERIMENTS, $\gamma > 10^{-4}$

Improvements: ground plane
Simple idea:
The ground plane acts as a capacitor shunting the environmental noise.
Single NIS junction in resistive environment

\( P(E) \) in low resistance environment:

\[ I \approx \frac{1}{e^2 R_T} \int_{-\infty}^{\infty} dE n_{\text{eff}}(E) \left[ f_N(E - eV) - f_S(E) \right] \]

with

\[ n_{\text{eff}}(E) = \frac{1}{\pi} \int_{|\epsilon| \geq 1} d\epsilon \frac{|\epsilon|}{\sqrt{\epsilon^2 - 1}} \frac{\gamma}{\gamma^2 + (\epsilon - E/\Delta)^2} = |\text{Re} \frac{E/\Delta + i\gamma}{\sqrt{(E/\Delta + i\gamma)^2 - 1}}| \]

\[ \gamma = 2\pi R K_{\text{env}} k_B T_{\text{env}} / \Delta \]

Numerical IVs + Dynes model

Influence of capacitance
SINIS turnstile in dissipative environment (R-SINIS)

$R_{Cr} = 80 \, k\Omega$

S. Lotkhov et al., APL 95, 112507 (2009)
Harmonic vs rectangular drive

Square drive improves plateau quality; it avoids staying at degeneracy positions.
Latest generation of samples

0.32 um long island

1.3 um long island
Preliminary measurements on the new samples (1.11.2009)

$\eta = 2 \times 10^{-5}$

$f = 50$ MHz
Ultimate tests of the accuracy

Counting electrons in the box:
Pumping at 100 Hz
RF-refrigeration

Question: can one cool the island of a single-electron box by gate?
Typical cooling cycle

\[
\langle Q^\pm \rangle \sim \mp k_B T
\]


Influence of photon assisted tunneling: N. Kopnin et al., PRB 77, 104517 (2008)
RF-refrigerator - experiment

S. Kafanov et al., PRL 103, 120801 (2009)
Results of the cooling experiments

DC current provides thermometry for both DC and RF cooling

\[ \Gamma^- / \Gamma^+ = e^{-eV/kT} \]

\[ eV \]

RF cooling

DC cooling

![Graphs showing cooling effects with different frequencies](image)
Summary on the turnstile

Simple design and operation

Errors can be suppressed efficiently by:
  - low $T$
  - large $E_c$
  - optimized waveforms
  - environment engineering
  - improved junction quality

Straightforward to run many turnstiles in parallel to increase current - now > 100 pA using 10 turnstiles

Performance can be improved by self-cooling

Possibility for error counting and correction

Presently $10^{-4}$ accuracy and > 100 pA
extras
Evidence for Andreev "leakage"?
Frequency dependence: missed-tunnelling errors

Missed tunnelling events due to high frequency:

$$\frac{\delta N}{N} \sim \exp\left(-\frac{E_C}{e^2 R_T \omega}\right)$$

Similar cut-off frequency as in normal pumps. Here it influences the rise onto the step, which is not the most critical issue as such.