Reaching metrological accuracy with the SINIS single-electron turnstile

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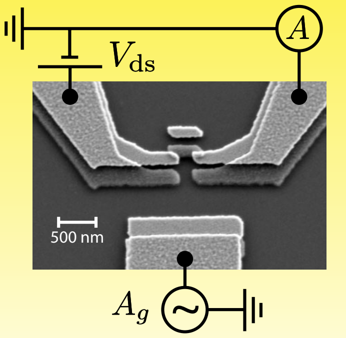
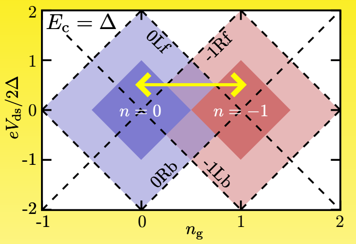
The SINIS turnstile

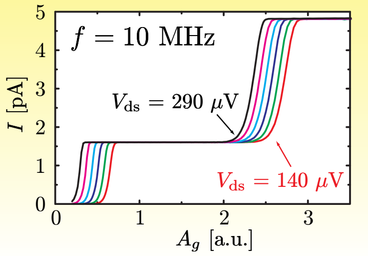
Hybrid single-electron transistor can be used as an accurate electron pump. Promising candidate for a quantum standard of electric current.



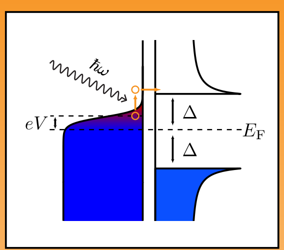
DC bias voltage establishes a preferred tunneling direction. Integer number of electrons are transferred in each cycle of RF drive signal.

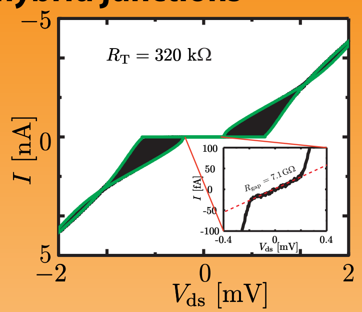


Interplay between superconducting gap Δ and charging energy $E_c = e^2/2C$ creates hysteresis in charge states.



Charge transport in hybrid junctions





First-order quasiparticle tunneling dominates charge transport in hybrid structures with sufficiently opaque tunnel junctions. Orthodox theory expression for the tunneling rate reads

$$\Gamma(\delta E) = \frac{1}{e^2 R_T} \int\int \mathrm{d}E\,\mathrm{d}E'\, n_S(E) f_S(E) \left[1 - f_N(E')\right] P(E - E' - \delta E),$$

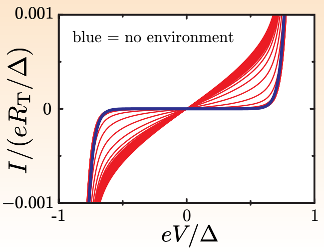
$$n_S(E) = \left|\mathrm{Re}\left[\frac{E/\Delta}{\sqrt{(E/\Delta)^2 - 1}}\right]\right| \qquad f_{N(S)}(E) = \left[1 + \exp(E/k_B T_{N(S)})\right]^{-1}$$

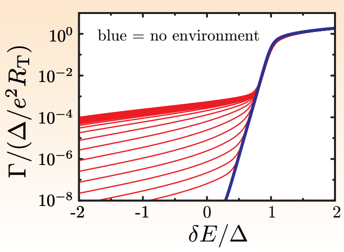
The operating principles of SINIS devices can be well understood by assuming no energy exchange with the electromagnetic environment. However, environmental fluctuations are crucial for explaining deviations from the ideal behavior, e.g., the error rate of the electron turnstile. The effect of equilibrium environmental fluctuations is described by P(E) theory.

$$J(t) = 2\int_0^\infty \frac{\mathrm{d}\omega}{\omega} \frac{\mathrm{Re}(Z_t(\omega))}{R_K} \left\{\coth\left(\frac{\hbar\omega}{2k_B T}\right) \left[\cos(\omega t) - 1\right] - i \sin(\omega t)\right\}$$

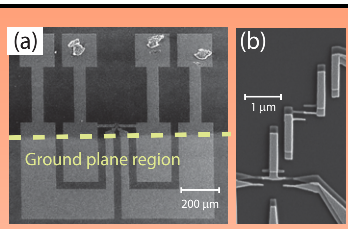
$$P(E) = \frac{1}{2\pi\hbar} \int \mathrm{d}t \exp\left[J(t) + \frac{i}{\hbar} E t\right]$$

Below, we demonstrate the effect of a hot RC environment on the I-V curves and first-order tunneling rates of an NIS junction.





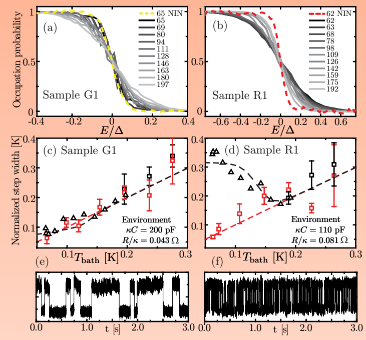
Experimental results

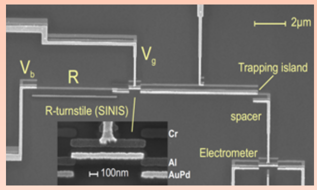


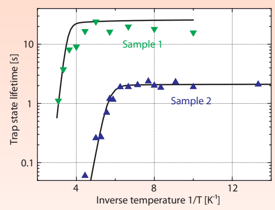
Environmental activation of first-order tunneling demonstrated by real-time detection of the charge state of a galvanically isolated hybrid single-electron box.

Anomalous behavior of Coulomb step widths at low temperatures as predicted by P(E) theory in samples with strong coupling to environmental noise.

Filtering of high-frequency noise by an on-chip capacitive shunt results in reduction of the environmentally activated tunneling rates by an order of magnitude.

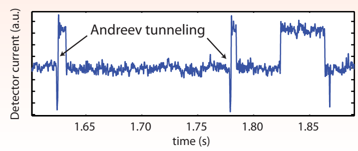






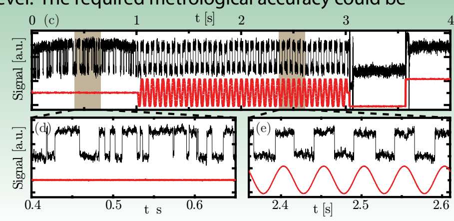
Large series resistor also works as a low-pass filter. Low temperature saturation of hold times in an R-SINIS electron trap is in agreement with a P(E) theory calculation where high-temperature environment and the on-chip resistor are treated as separate fluctuators.

In a hybrid single-electron box with low charging energy, it is also possible to study Andreev events in real time using similar techniques as above.



Counting experiment for a definitive measurement of turnstile accuracy

Metrological applications call for a current standard with an error rate of 10^{-7} or better at 100 pA current level. The required metrological accuracy could be demonstrated rigorously by performing a counting experiment, where pumped charges, or alternatively only the error events, are individually detected. Figure shows controlled electron transfer at 20 Hz.



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