Applications of single electron devices

Current and capacitance standards
Electrometers - the scanning SET
Thermometry
Intro to the rf-SET

Metrology

We’ve established that, for a variety of reasons, SEDs are unlikely to become mass-fabricated substitutes / replacements for MOSFETs in consumer technology.

What are they good for?

Niche applications like *metrology*.

Gadgets that are challenging to fabricate and require moderately extreme conditions to operate are common in precision metrology:

- Atomic clocks (UHV, temperature control)
- Quantum Hall resistance standard (low $T$, high $B$)
Current and capacitance standards

Primary standards for electrical units exist for voltage and resistance:

**Voltage** = Josephson effect
- Superconductor-insulator-superconductor junction.
- Applied ac current at frequency $f$ produces dc voltage steps of size $nhf / 2e$.
- Constant: 483597.9 GHz/V

**Resistance** = integer quantum Hall effect
- 2d system, high magnetic field.
- Hall resistance is quantized to fractions of $h/ne^2$.
- Constant: 25812.807 Ω

A primary *current* standard would allow testing the “metrology triangle”:

- Quantum Hall: $R_H = h / ne^2$
- Josephson effect: $I = ef$
- Single-electron tunneling

These quantities had better all be consistent with one another, or there’s new physics somewhere….

Effectively would provide another check on the value of the fine structure constant.
Current standard: SET pump

Recall the basic idea here. Cycling voltages around one of the “triple points” in the diagram at the lower right should transfer a single electron (on average) through the pump, right to left. (Thus a unidirectional current from left to right….)
Current standard: SET pump

Actual experimental data on 2-gate pump agrees with this. Current is nonzero only in vicinity of “triple points”.

Three junction two island pump errors in experiment: ~1%.

Error sources:
• thermal hopping
• “missed” tunneling events
• cotunneling

Current standard: SET pump

One approach to dealing with these errors: more junctions!

State-of-the-art: NIST seven-junction six-gate pump.

Really designed for low frequency work - electron counting rather than current standard.

Errors with this set up: ~1.5 x 10^-8.

Much better, but very challenging….
Capacitance standard

Even slow pumping of electrons can be very useful.

Capacitance standard:

- Make a capacitor.
- Pump a precisely known number of electrons onto the capacitor (e.g. with the 7-junction pump).
- Measure the capacitor voltage precisely.
- $Q = CV$ gives the capacitance.


Here is the measured voltage change after moving $117\,440\,513$ electrons on and off the capacitor repeatedly.

The reproducibility is very good, and the NIST team measured their little cryogenic capacitor to be $C = 1.872\,484\,77\,\text{pF}$.

Biggest problem: long term stability due to motion of offset charges in $\text{Al}_2\text{O}_3$ tunnel barriers.

Can be improved by working with Si SETs instead.
Electrometry

Current flow through SET can be modulated between maximum and minimum values by moving a single electron off and on the gate:

\[ \frac{G}{G_{\text{max}}} = \cosh^{-1} \left[ \frac{e(C_s / C_{eq}) \cdot (V_g^0 - V_g)}{2.5k_B T} \right] \]

One possible generalization: have the island be a moveable probe!

As the island capacitively couples to test objects, its polarization charge \( Q_p \) changes.

This shifts the \( G \) vs. \( V_G \) plot at right. From our SET analysis, \( V_G^0 \equiv V_0 + Q_p / C_s \).

Sensitivity limits possible: \( < 10^{-5} \, e/\text{Hz}^{1/2} \)

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Electrometry

Basic idea:

Bias gate voltage to point where \( G \) vs. \( V_G \) is most rapidly varying.

Apply a small source-drain voltage to measure \( G \).

Then change the charge distribution near the island.

Small changes in \( V_0 \) lead to large changes in measured source-drain current.
One adaptation of this is to place the island on a movable tip, and scan it over a surface.

Result: the SET scanning electrometer (SETSE).

SETSE is easily sensitive enough to see surface charge fluctuations caused by individual dopant atoms in semiconductor.

Problems:
• slow
• fragile
• painful to fabricate
• requires quite low $T$. 

Image from Bell Labs
Coulomb blockade thermometry

Remember that a single junction (or for that matter, an array of junctions), when voltage biased, leads to an IV curve that looks like:

\[ I \]
\[ V_{\text{offset}} \]
\[ V_c \]
\[ V \]
\[ dI/dV \]

The theory has been done for what this “zero-bias anomaly” looks like as a function of temperature for a 1d array of tunnel junctions.

\[ G/G_T = 1 - (e / k_B T) g(eV/Nk_B T) \]

\[ V_{1/2} = 5.439 Nk_B T / e \]

\[ \Delta G/G_T = e / 6k_B T \]

Primary thermometer

Secondary thermometer

Normalised conductance, \( G/G_T \), of a CBT sensor against bias voltage \( V \). The theoretical curve is shown as a black line.

\[ g(x) = [x \sinh(x) - 4 \sinh^2(x/2)] 8 \sinh^4(x/2) \]
Coulomb blockade thermometry

- Can improve reliability by having parallel 1d arrays.
- 2d arrays also work, with essentially identical function for ZBA width (though high temperature corrections are different).
- Work from 30 K down to < 20 mK, with basically no $B$ dependence and comparatively low power dissipation!

Intro to rf-SET

Our analysis of SETs has all been done at dc.
Is it possible to use SET at high frequencies, also? Yes.
One approach: Reflection rf-SET

Reflection rf-SET
Intro to rf-SET

Basic idea:
- rf impedance of SET also changes periodically in gate voltage.
- Make resonator, send in known rf power, and monitor changes in reflected power as impedance mismatch is varied by SET impedance changes.
- Since rf carrier can be at a high frequency (1.7 GHz), it should be possible to see rapid amplitude modulations (MHz).
- Sensitivity can still be incredibly high.

Using rf-SET electrometer, Prof. Rimberg can “watch”, in real time, as individual electrons tunnel on and off a quantum dot!

rf-SET and Quantum Dot

Have made an rf-SET strongly coupled to a GaAs/AlGaAs quantum dot.
Resonates at ~ 1 GHz.
Can mix reflected wave with incident wave to demodulate.
When QD leads are very closed, can see discrete changes in rf-SET offset charge betw/ two states.
rf-SET and Quantum Dot

Have shown that number of transition events has peaks at same QD gate voltages that give QD Coulomb blockade peaks.

Strongly suggests that rf-SET is measuring individual $e^-$ on the QD.

Varying QD gate changes preferred state of QD (e.g. usually charge $n$, vs. usually charge $n+1$).


Can see transition rate pick up as QD source-drain bias is increased.

Can also monitor fluctuations.

In principle, can acquire complete statistical information about current flow!

Great potential applications for quantum computation, for example.
Summary:

• While SETs are unlikely to replace regular FETs for a number of reasons, they can find excellent utility in niche applications, particularly metrology.

• Single electron pumps can be used for fundamental physics tests + defining current and capacitance standards.

• SET electrometers can be incredibly sensitive, allowing unprecedented precision measurements of surface potentials and charges, possibly even in real time.

• Coulomb blockade devices can also be used as precision thermometers.