Single-electronics & Nano-mechanics: Towards Quantum-limited Motion Detection

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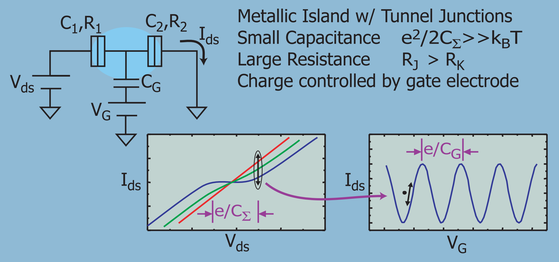
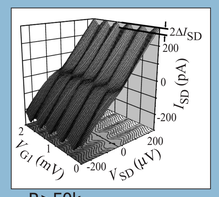
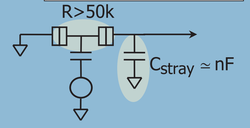
Single Electron Transistors



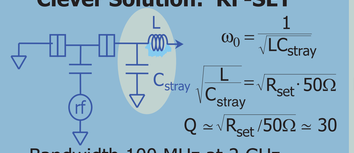
Metallic Island w/ Tunnel Junctions
Small Capacitance $e^2/2C_\Sigma >> k_BT$
Large Resistance $R_J > R_K$
Charge controlled by gate electrode





RC_{stray} forms a filter
use < few kHz
Possible solution:
-Use adjacent preamp to match impedance

Clever Solution: RF-SET



$$\omega_0 = \frac{1}{\sqrt{LC_{stray}}}$$

$$\sqrt{\frac{L}{C_{stray}}} = \sqrt{R_{set} \cdot 50\Omega}$$

$$Q \simeq \sqrt{R_{set}/50\Omega} \simeq 30$$

Bandwidth 100 MHz at 2 GHz

Problems:

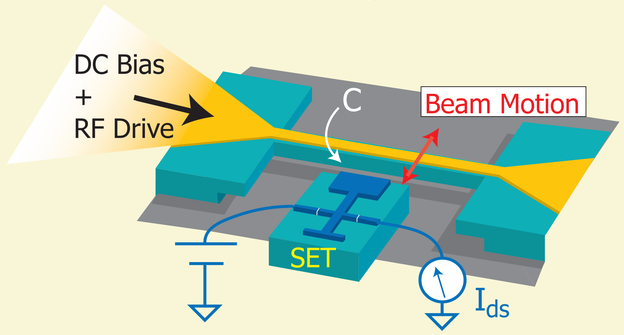
Need to guess L right
-apriori freq. unknown

Frequency fixed by circuit
-not tunable

Getting RF out of fridge
-cryogenic preamp

Schoelkopf, et al Science **280**, 1238

Capacitive coupling of SET to nano-mechanical resonator



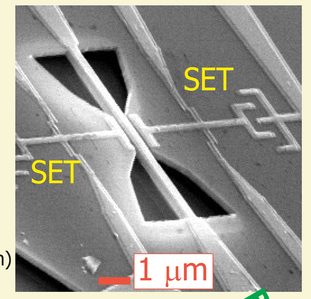
Blencowe & Wybourne, APL **77** 3846.

Beam motion Δx changes C, modulates I_{sd} at ω_{beam}

For $\delta q = 1.5\ 10^{-5}\ e/Hz^{1/2}$

GaAs (3μm*200nm*200nm)
ω_{beam}=100 MHz

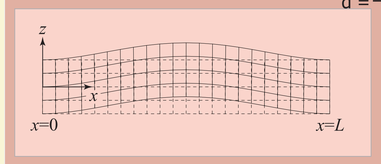
Displacement sensitivity:
$\delta x \simeq 10^{-13}\ m/Hz^{1/2}$

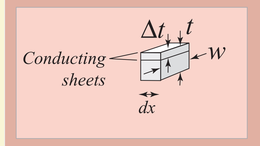


Piezo-electric detection

Dielectric materials develop electric field when strained (eg. GaAs, AlAs)

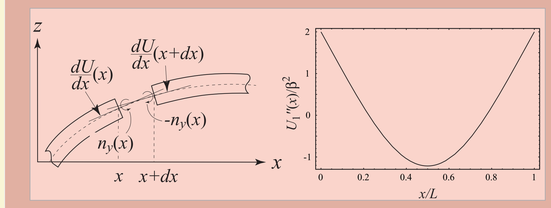
$$d = \frac{2.69\ pC/m^2}{2} \begin{Bmatrix} 0 & 0 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 2 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \end{Bmatrix}$$





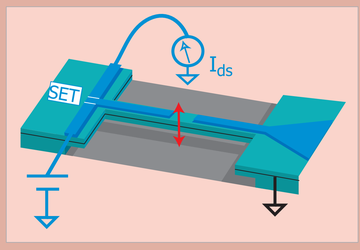
Use buried two-dimensional electron gas as ground plane

Electric potential develops between top surface and 2DEG



Voltage developed:

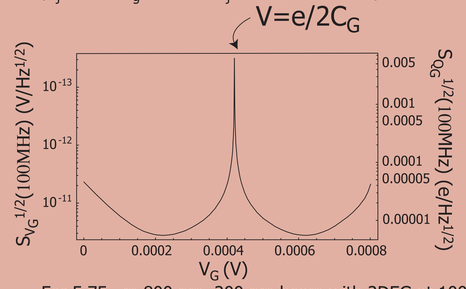
$$V = \frac{d_{14}\, E\, t\, \Delta t}{4\varepsilon\varepsilon_0} \quad AU''(x)$$



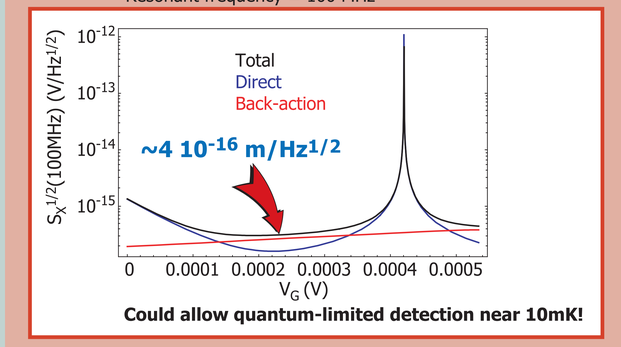
Piezoelectric field between electrode and buried 2DEG modulates gate charge on SET

Use rf-SET or SET mixer for high frequencies

SET sensitivity in "Orthodox Theory"
(C_j = 1 fF, C_g=200 aF, R_j=50kΩ, T= 30 mK)

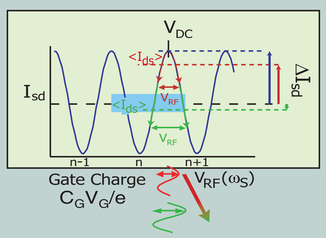


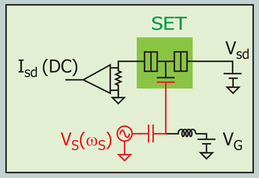
For 5.75 μm 800 nm 200 nm beam with 2DEG at 100nm deep
Resonant frequency = 100 MHz



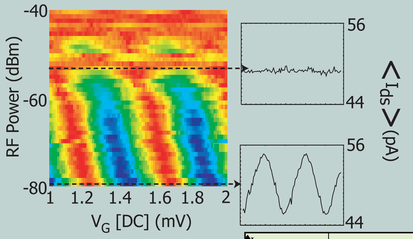
The Single Electron Transistor As a Radio Frequency Mixer

Homodyne Detection

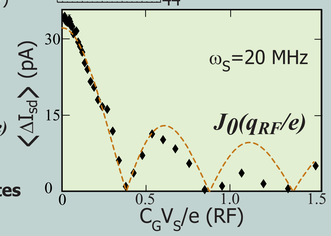




RF on gate **averages** over curve **reduces** I_{sd}(DC)

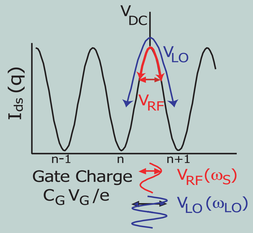


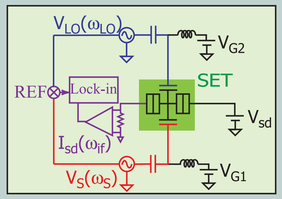
DC Current w/ varying RF Voltage

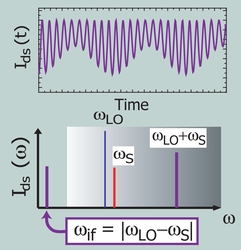


Bessel function $J_0(q_{RF}/e)$ for sinusoidal $I_{ds}(V_G)$.

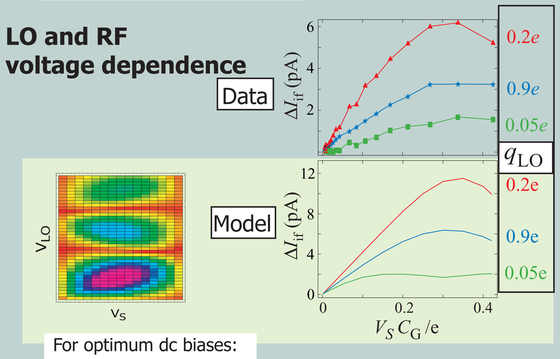
Confirms and calibrates RF gate action







LO and RF voltage dependence



For optimum dc biases:

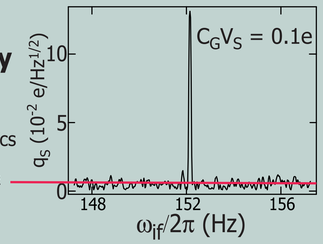
$$\Delta I_{if}(V_S, V_{LO}) = 2\Delta I_0\, J_1(2\pi C_G V_S/e)\, J_1(2\pi C_G V_{LO}/e)$$

Current gain:

$$\Delta I_{if} = g_I\, I_S \simeq 3.66\, \Delta I_0\, C_G V_S/e = 1.83\, (\omega_{MAX}/\omega_S)$$

Mixer Sensitivity

Room temperature electronics limited background noise
$5\ 10^{-3}\ e/Hz^{1/2}$



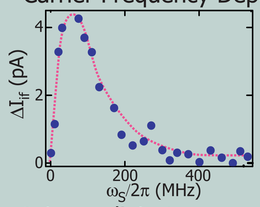
Theoretical shot noise limits

For this device, $S_q(\omega) \simeq 1.3\ 10^{-4}\ e/Hz^{1/2}$

For optimized device {C_Σ=1 fF, R=2R_K},
$S_q(\omega) \simeq 1.5\ 10^{-5}\ e/Hz^{1/2}$

1/f noise? Backaction?

Carrier Frequency Dependence



Works up to ~ 300 MHz
- limited by: external filters, $\omega_{MAX} = I_{sd}/e$

Low frequencies filtered to control aliasing.

Intermediate Frequency Depedence

Roll off due to RC time constant with parasitic capacitance

$$2\pi\Delta\omega = 250\ Hz$$

May be increased with rf-set or preamp