University of Basel
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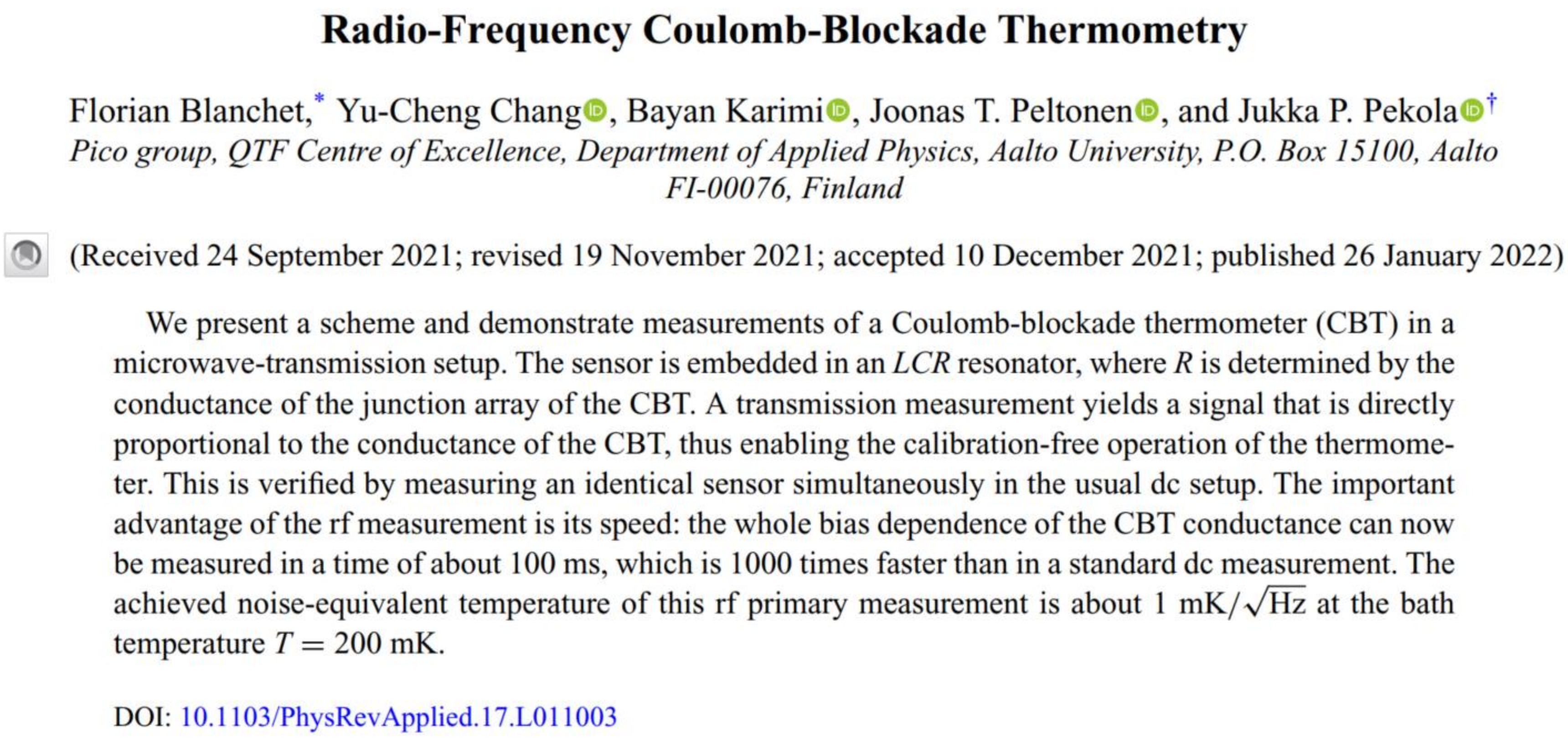
FAM talk

Christian Scheller



Radio-Frequency Coulomb-Blockade Thermometry

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We present a scheme and demonstrate measurements of a Coulomb-blockade thermometer (CBT) in a microwave-transmission setup. The sensor is embedded in an LCR resonator, where R is determined by the conductance of the junction array of the CBT. A transmission measurement yields a signal that is directly proportional to the conductance of the CBT, thus enabling the calibration-free operation of the thermometer. This is verified by measuring an identical sensor simultaneously in the usual dc setup. The important advantage of the rf measurement is its speed: the whole bias dependence of the CBT conductance can now be measured in a time of about 100 ms, which is 1000 times faster than in a standard dc measurement. The achieved noise-equivalent temperature of this rf primary measurement is about 1 mK/$\sqrt{\text{Hz}}$ at the bath temperature $T = 200$ mK.

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Deep Coulomb Blockade

Coulomb blockade thermometer

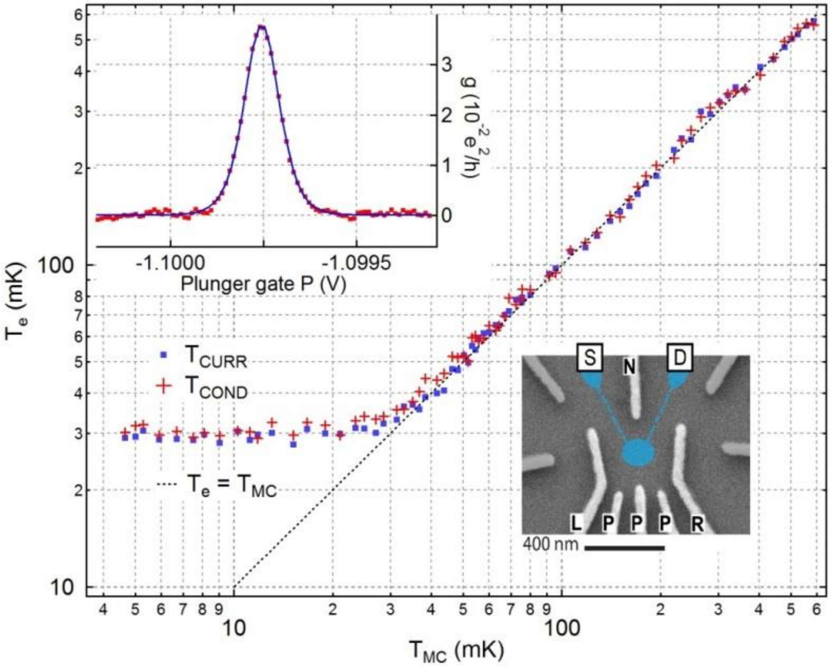
Coulomb blockade

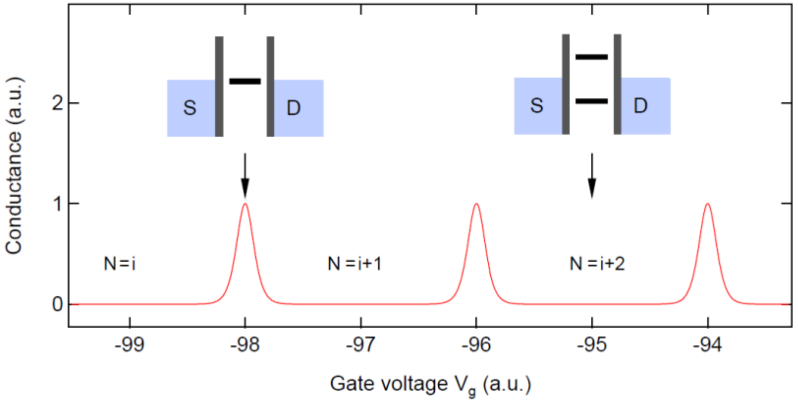
- Isolated charge, Capacitance to environment ⇒ charging E_C
- Energy eV ~ Temperature k_BT
- Tunnel rate: $\delta E \cdot \delta t > h$ (charging time RC, energy $E_C = e^2/C \Rightarrow$ R~25.8kΩ)

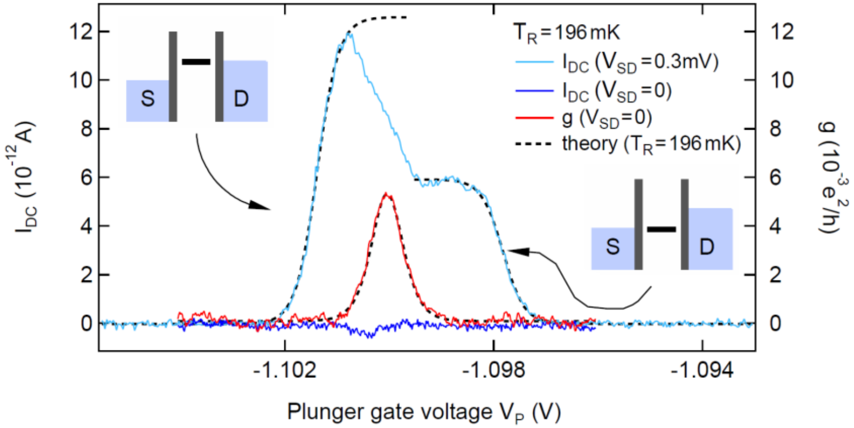
Deep Coulomb blockade $k_BT \ll E_C$

Thermometry requirement

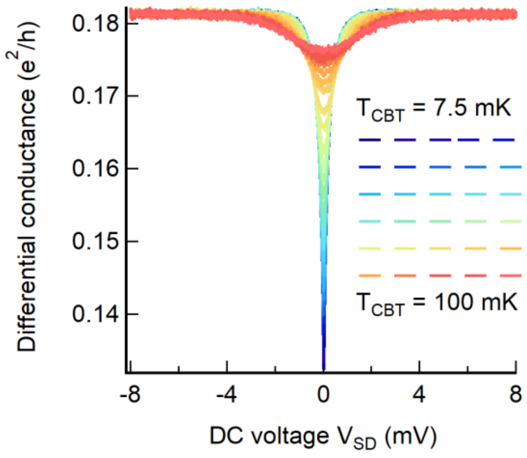
- Tunnel rate: $\Gamma \ll \frac{k_BT}{h}$ (small currents at low T !!!)
- AC measurement: $eV \ll k_BT$

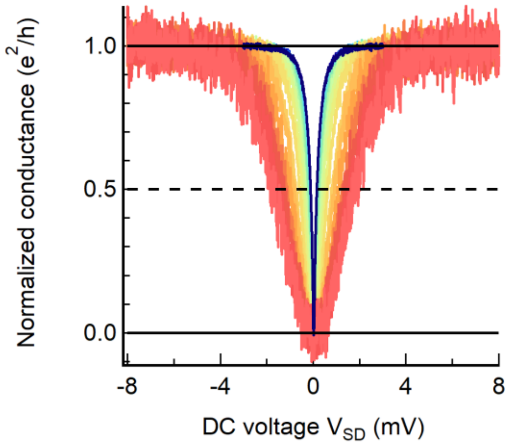






Weak Coulomb Blockade

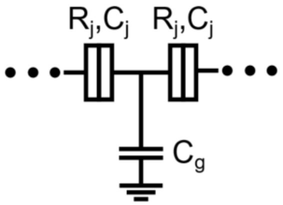




CBT: Coulomb blockade thermometer

- 2D Array of "small" metal islands with tunnel-junctions in-between
- Finite Capacitance $C_\Sigma \Rightarrow E_C = \frac{e^2}{2 \cdot C_\Sigma}$ Energy eV ~ Temperature k_BT
- For $T \gtrsim E_C$ zero bias suppression (charging effects)

$$C_\Sigma = 2C_j + C_g$$



Universal regime

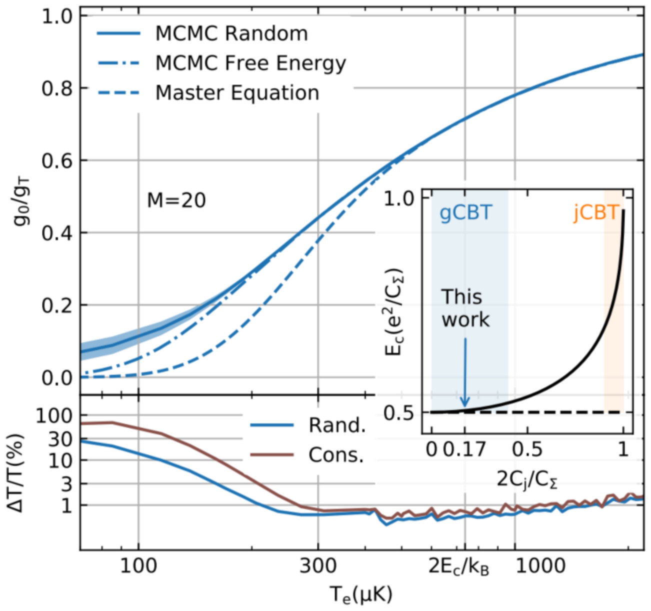
- No gate for CBT islands => "random" offset charge on each island
- For $k_BT > 0.8E_C$ universal conductance suppression

Primary thermometer:

- Width $eV_{1/2} = 5.4392\ Nk_BT$ (in absence of bias heating)

Secondary mode operation:

- Depth $\delta g \approx \frac{1}{6}u - \frac{1}{60}u^2 + \frac{1}{630}u^3$; $u = \frac{2E_C}{k_BT}$ (high-T calibration → charging energy EC)



RF CBT setup

CBT Devices

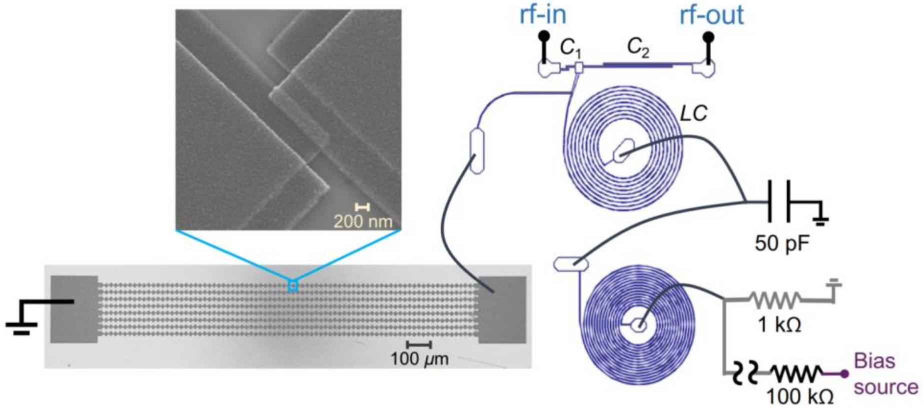
CBT100_dc:	100 kΩ,	classic	DC	100 junction, 10 row
CBT80_dc:	80 kΩ,	AlMn	DC	80 junction, 8 row
CBT80_rf:	80 kΩ,	AlMn	RF	80 junction, 8 row

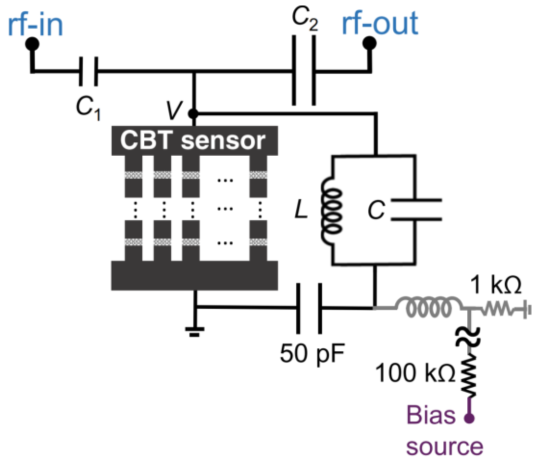
LCR tank circuit

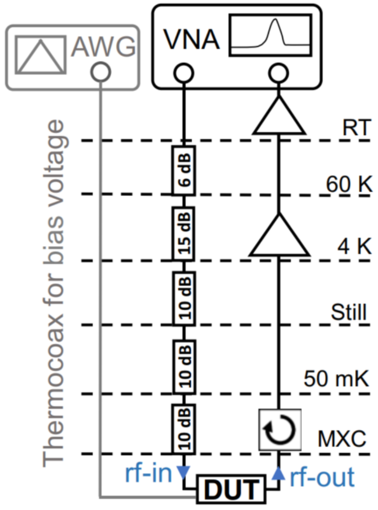
- Tank: f_0 = 547 MHz, Q = 45, $t_R=(Q/2\pi f_0)$=13ns
- Nb inductor: L = 110 nH (200nm sputtered onto high-R Si wafer)
- Capacitance C = 540 fF (C1=67 fF, C2=170 fF)
- Attenuation: 51dB (all stages → thermalization)
- Amplification: HEMT @ 4.2K
- Circulator: 480-720MHz BW, 20dB isolation
- Drain: CBT hard ground at LT

Sample fabrication

- 2 angle shadow mask patterned by e-beam
- Alloy target with 0.3% nominal Mn concentration
- Sequence: 20nm film of alloy, -45° tilt
  in-situ oxidation (pure O2, 10min)
  30nm film of alloy, +45° tilt
- Overlapp (junction): $1{,}2\mu m \cdot 180nm$
- Island: $15\mu m \cdot 15\mu m$
- Small island + weak ep-coupl. in AlMn
  ⇒ operation limited to T>200mK (overheating)







RF vs DC transport

RF measurement

Transmitted signal:

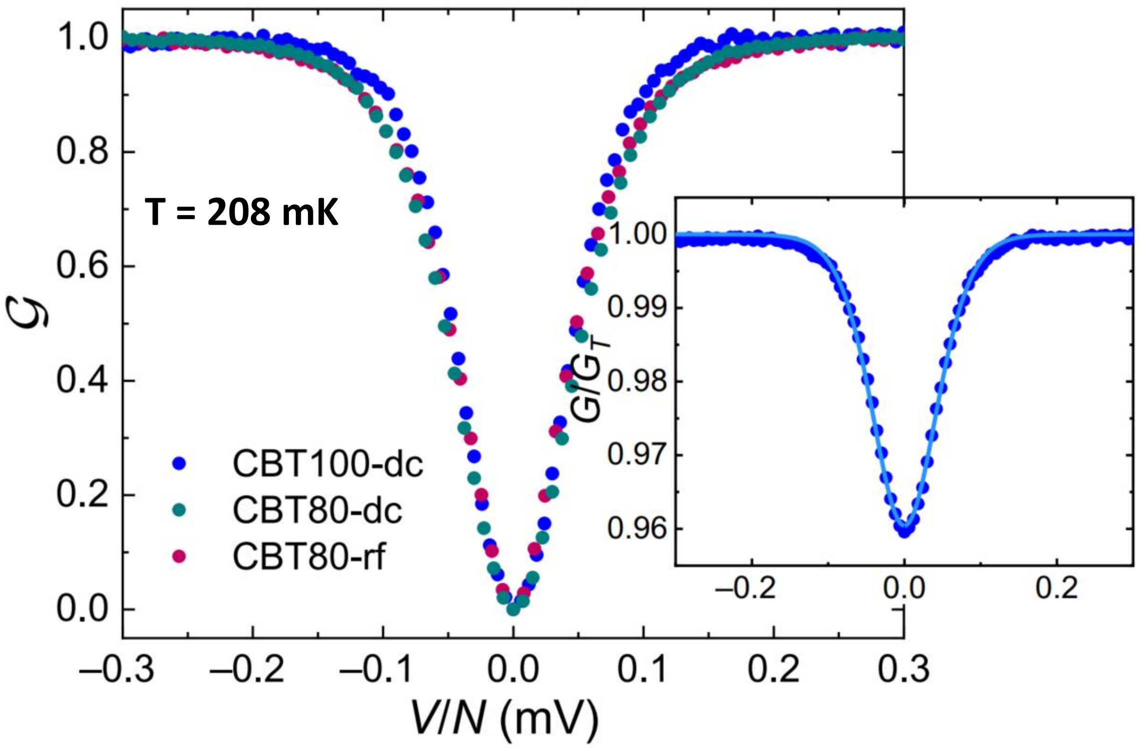
$$S_{21} = S_0 - 20\lg(1+R_0G)$$

$$R_0 \approx [R_L(2\pi f_0 C_2)^2]^{-1} \approx 59\,\mathrm{k}\Omega$$

$$R_L \approx 50\Omega$$

Linearize for dg/g<<1: $$S_{21} = \tilde{S}_0 - \frac{20}{\ln(10)}\frac{R_0G_T}{1+R_0G_T}\frac{G(V)}{G_T}$$

Precision: $1\ \mathrm{mK}/\sqrt{Hz}$
=> 2% precision @ 200 mK in 100ms



DC + Fit in inset:

Conductance dip with CBT fit → T_e, E_C

$$G(v)/G_T = 1 - u\,g(v) - \frac{u^2}{4}[g'(v)h'(v) + g''(v)h(v)]$$

$$g(v) = e^v[e^v(v-2)+v+2]/(e^v-1)^3$$

$$u = E_C/(k_BT)$$

$$v = eV/(Nk_BT)$$

$$h(v) = v\coth(v/2)$$

Normalized conductance: $$G' = \frac{G(V)-G(0)}{G_T-G(0)}$$

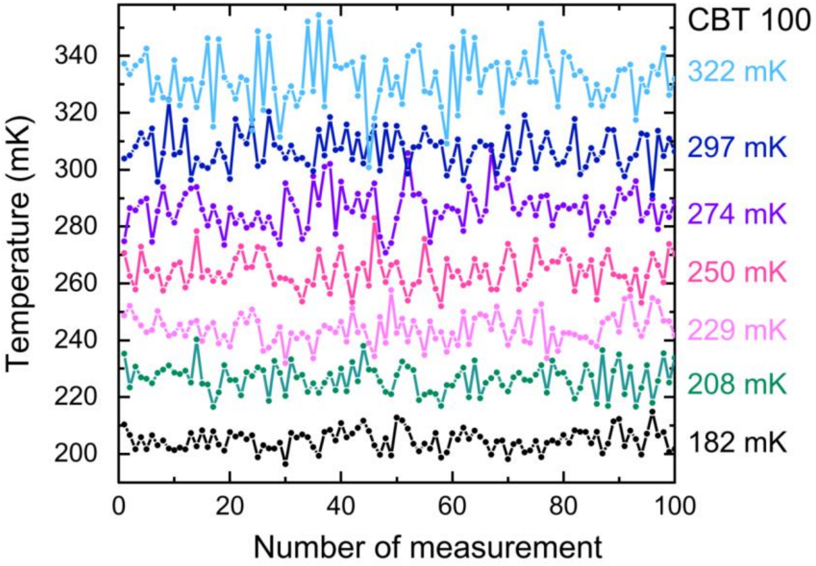
Motivation

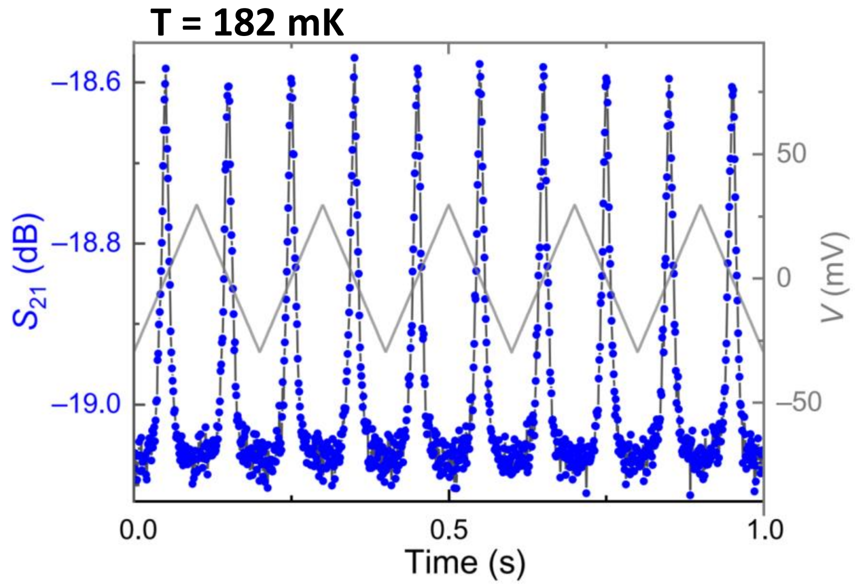
Fast DC bias-scans

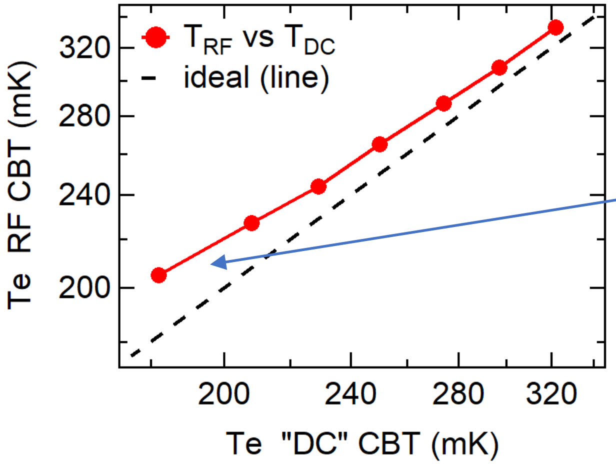
- Triangular $\pm 30\mathrm{mV}$ voltage ramp across device (AWG, 100ms half period)
- Sign inverted in S_{21}: dip → peak

RF vs "DC" temperature

- Qualitative agreement
- RF reads higher in general (RF heating effects ?)
- Plot T_{RF} vs T_{DC} would be nice !







Separation:
RF heating ?

Summary

- CBT measured @ 200 - 350 mK with tank circuit (547MHz)
- 100 ms acquisition time for DC sweep (1000 times faster)
- “Good” agreement between DC and RF measurement
- Probably overheating with RF (needs more work to be useful at low T)

- AlMn tunnel junction CBT developed: Works also at B=0 !!! (interesting for AND)