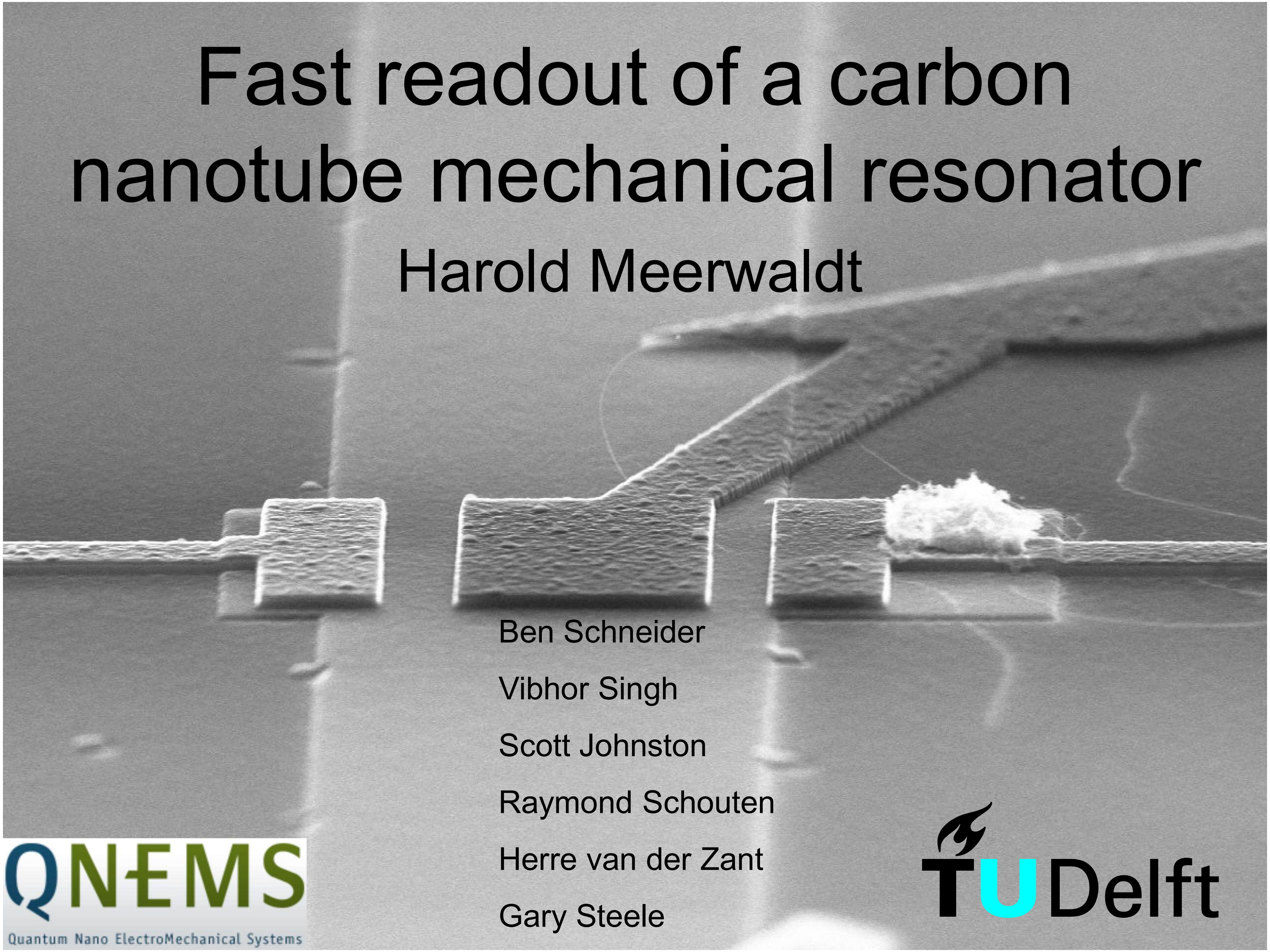
Fast readout of a carbon nanotube mechanical resonator

Harold Meerwaldt



Ben Schneider

Vibhor Singh

Scott Johnston

Raymond Schouten

Herre van der Zant

Gary Steele

QNEMS

Quantum Nano ElectroMechanical Systems

TU Delft

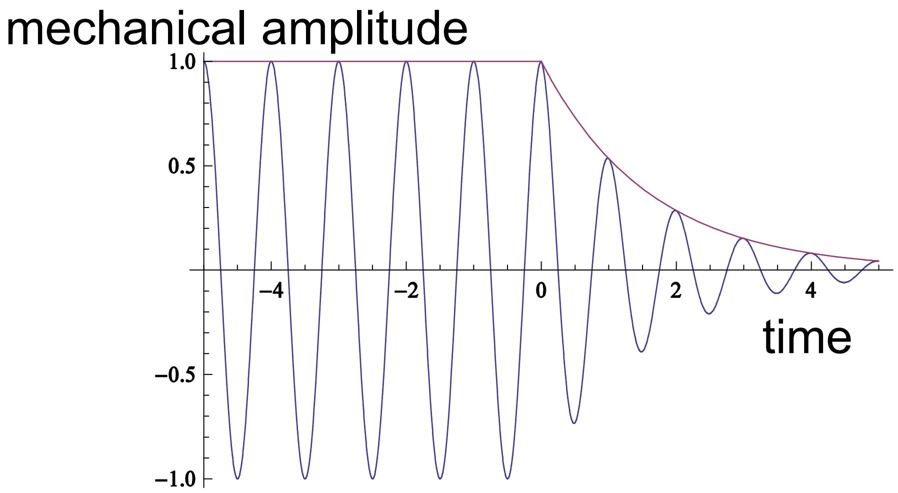
Conclusion

We have read out the mechanical motion of a carbon nanotube with submicrosecond time resolution.

Motivation: damping measurements

<u>ringdown measurement</u>

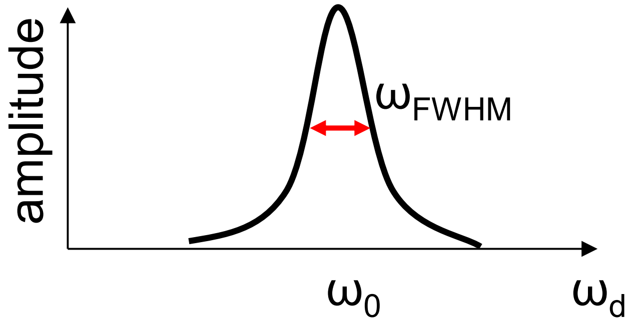
$Q_{ringdown} = \omega_0 \tau_{decay}/2$



not yet done in CNTs
due to bandwidth limitations

<u>spectral measurement</u>

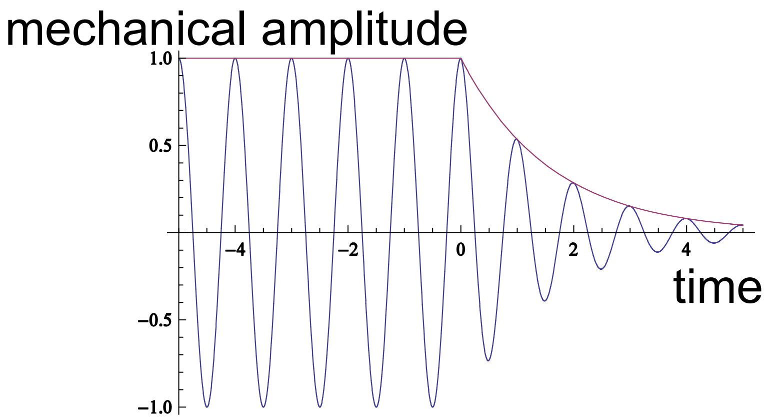
$Q_{spectral} = \omega_0/\omega_{FWHM}$



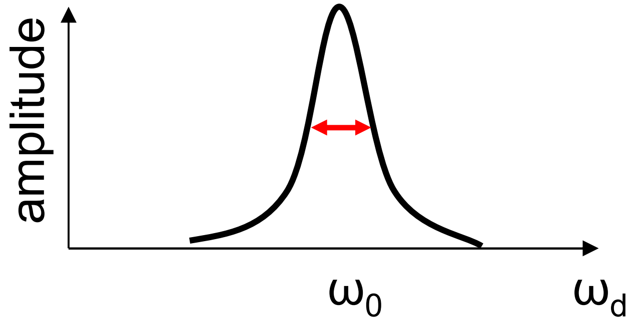
standard for CNTs

Quality factor contributions

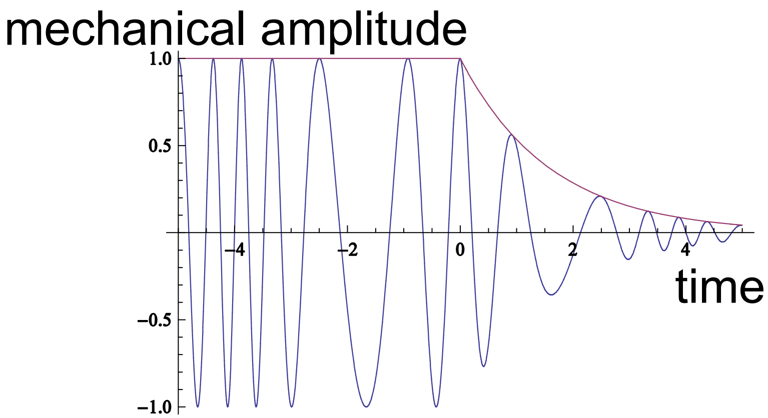
energy relaxation



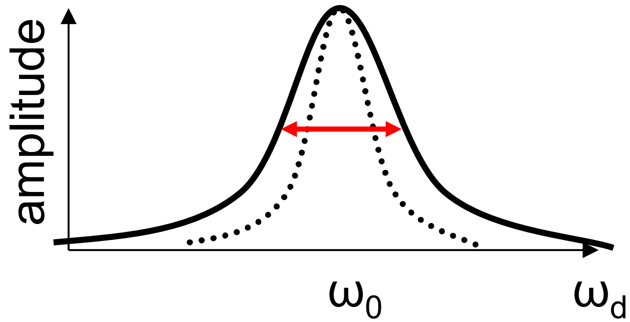
$Q_{spectral} = Q_{ringdown}$



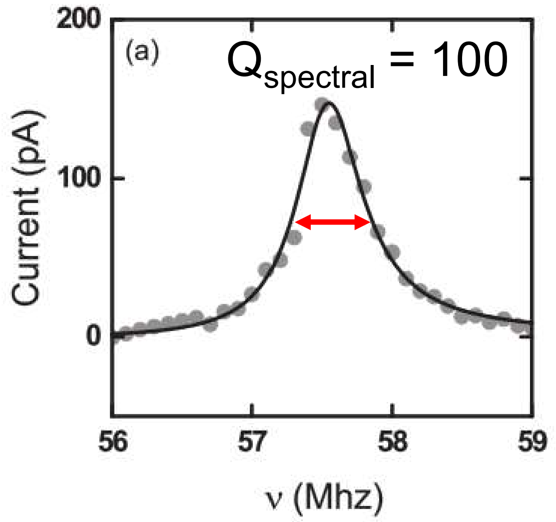
spectral broadening/excess phase noise



$Q_{spectral} < Q_{ringdown}$

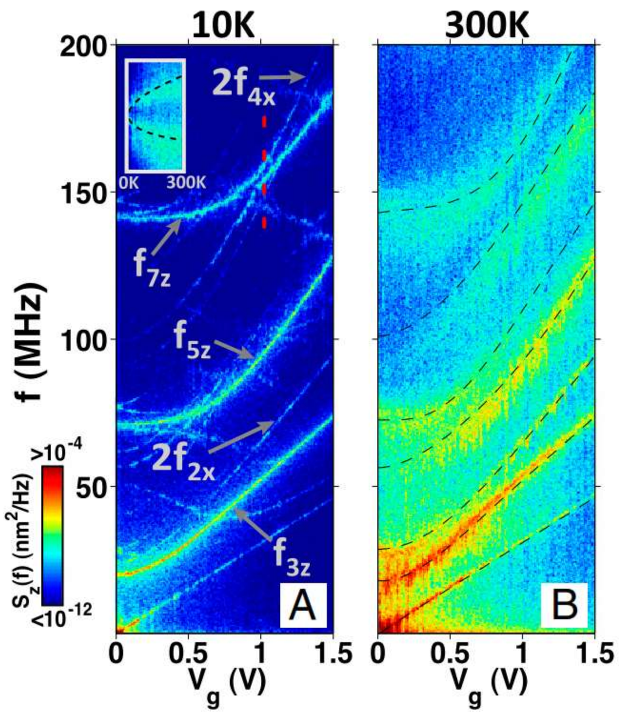


Spectral broadening in CNTs



Witkamp et al., NanoLett 2006

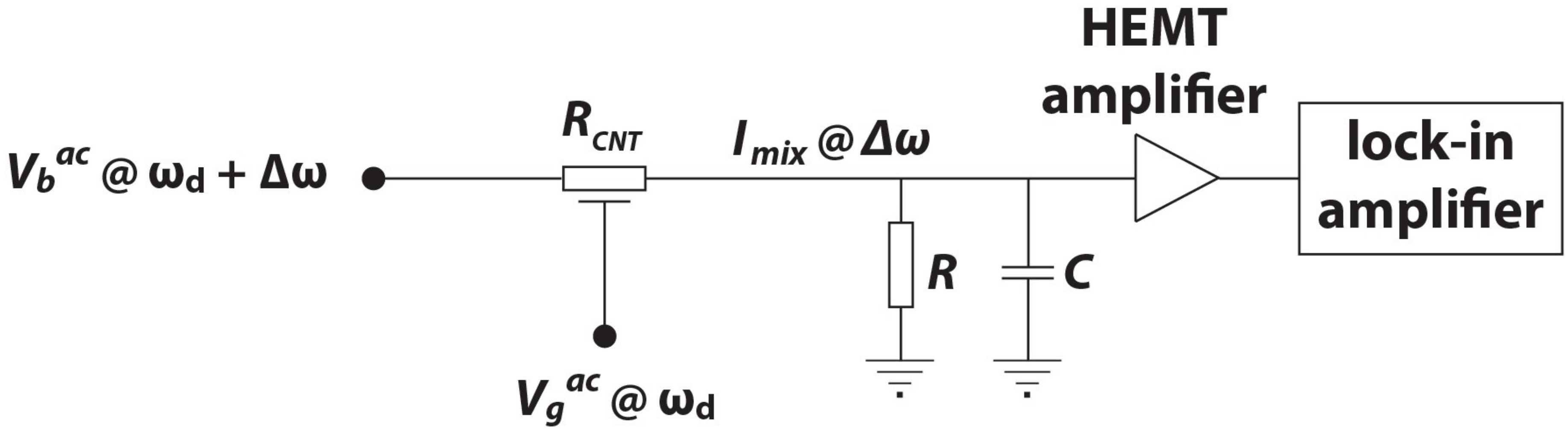
simulation



Barnard et al., PNAS 2012

- Low Q @ RT
- Mode coupling + thermal motion ➔ spectral broadening ($Q_{spectral} < Q_{ringdown}$?)

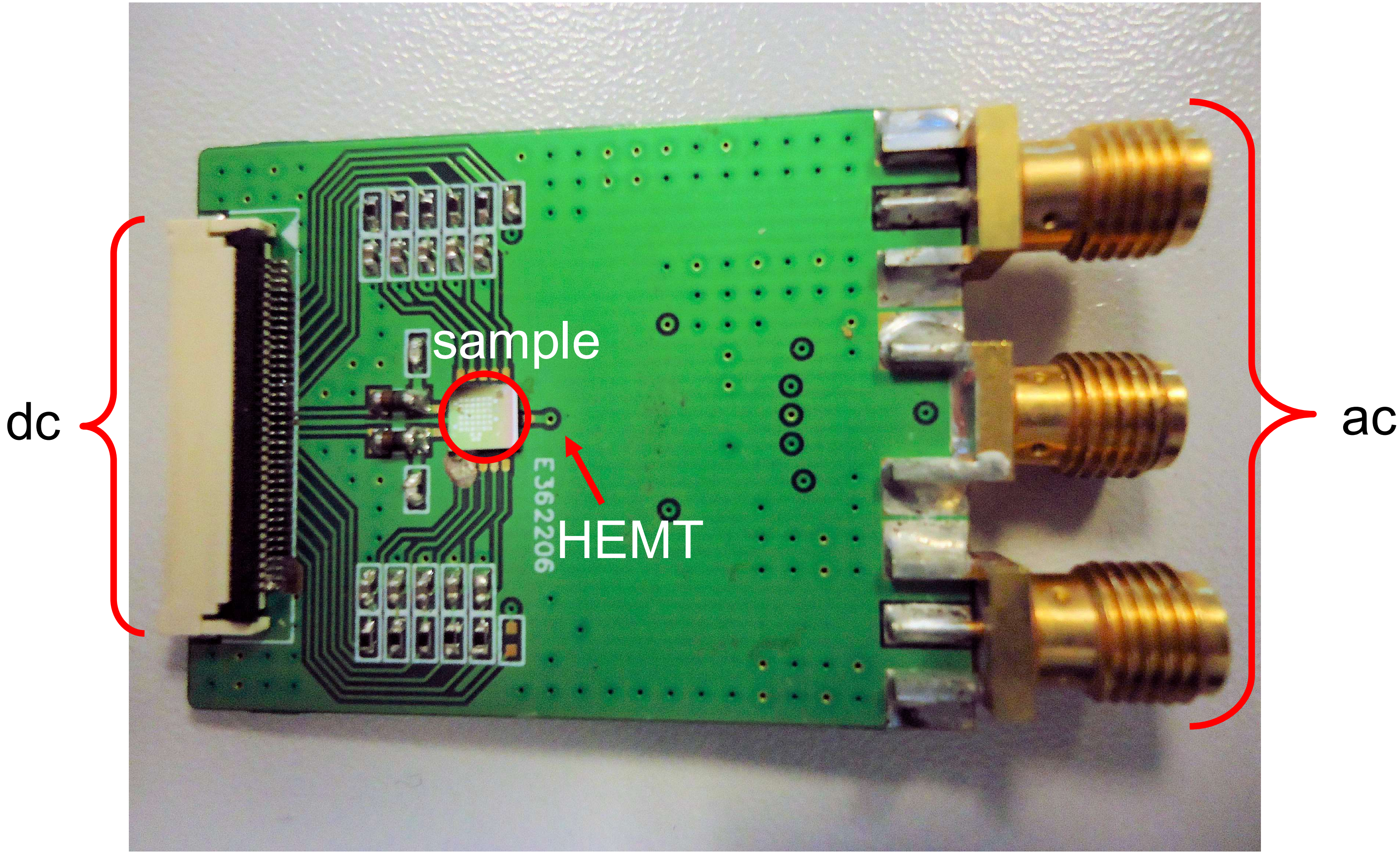
High-bandwidth measurement



- mechanical (and electrical) mixing $G^{\omega_d} \cdot V_b^{\omega_d+\Delta\omega} \Rightarrow I_{mix}^{\Delta\omega}$

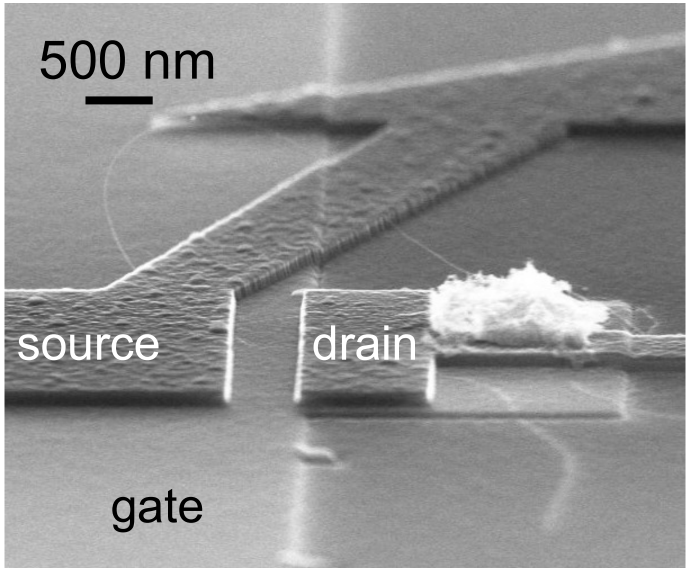
- a close-proximity amplifier
  - high-impedance
  - low power ➔ cryogenically compatible

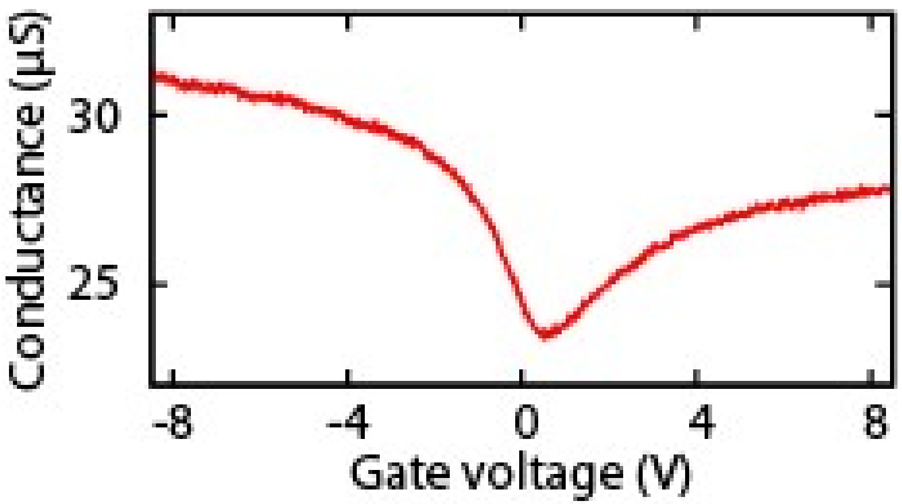
Close-proximity HEMT amplifier



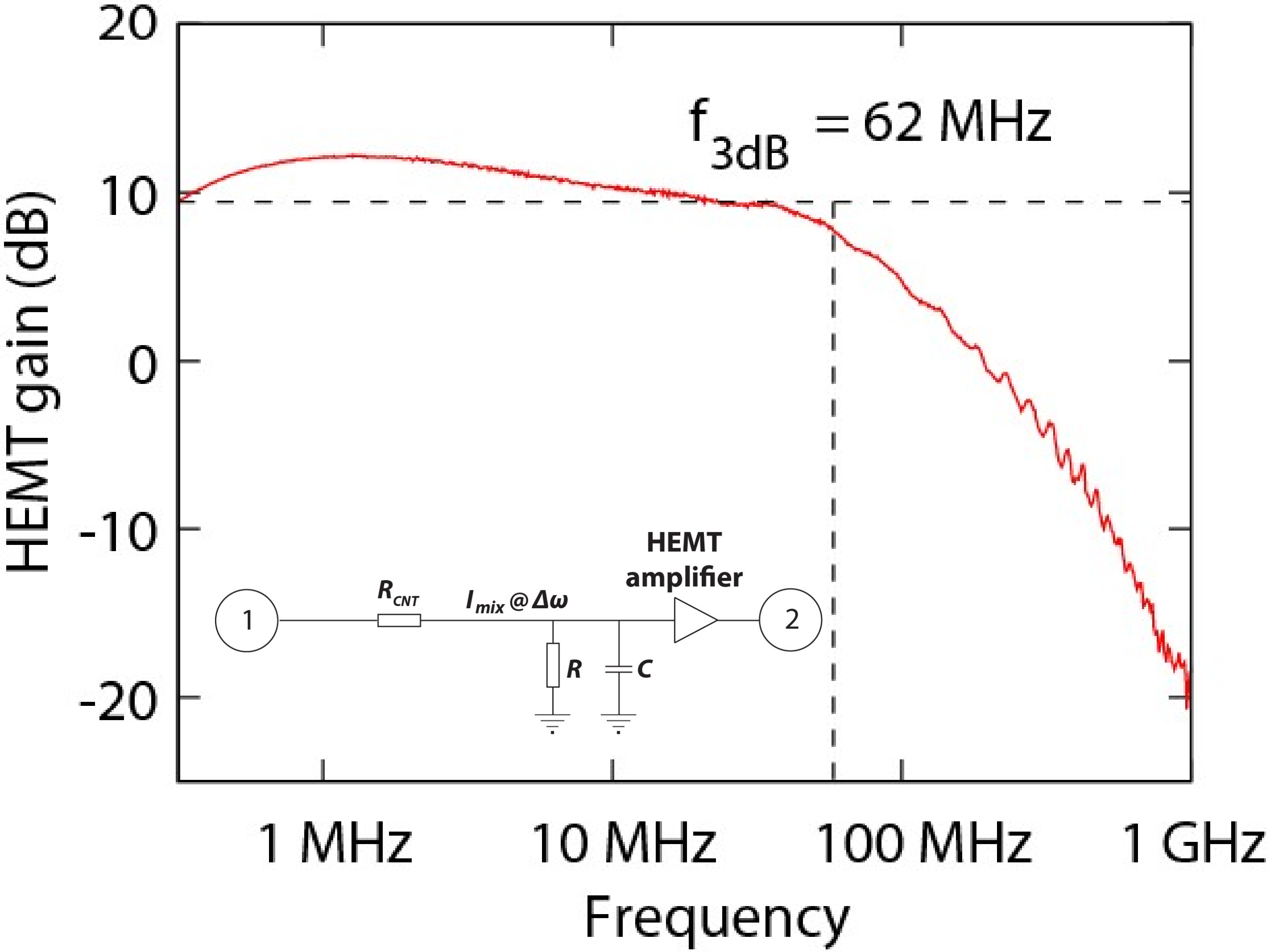
Device characteristics

- length: 700 nm
- separated ~200 nm from gate
- gate-dependent conductance

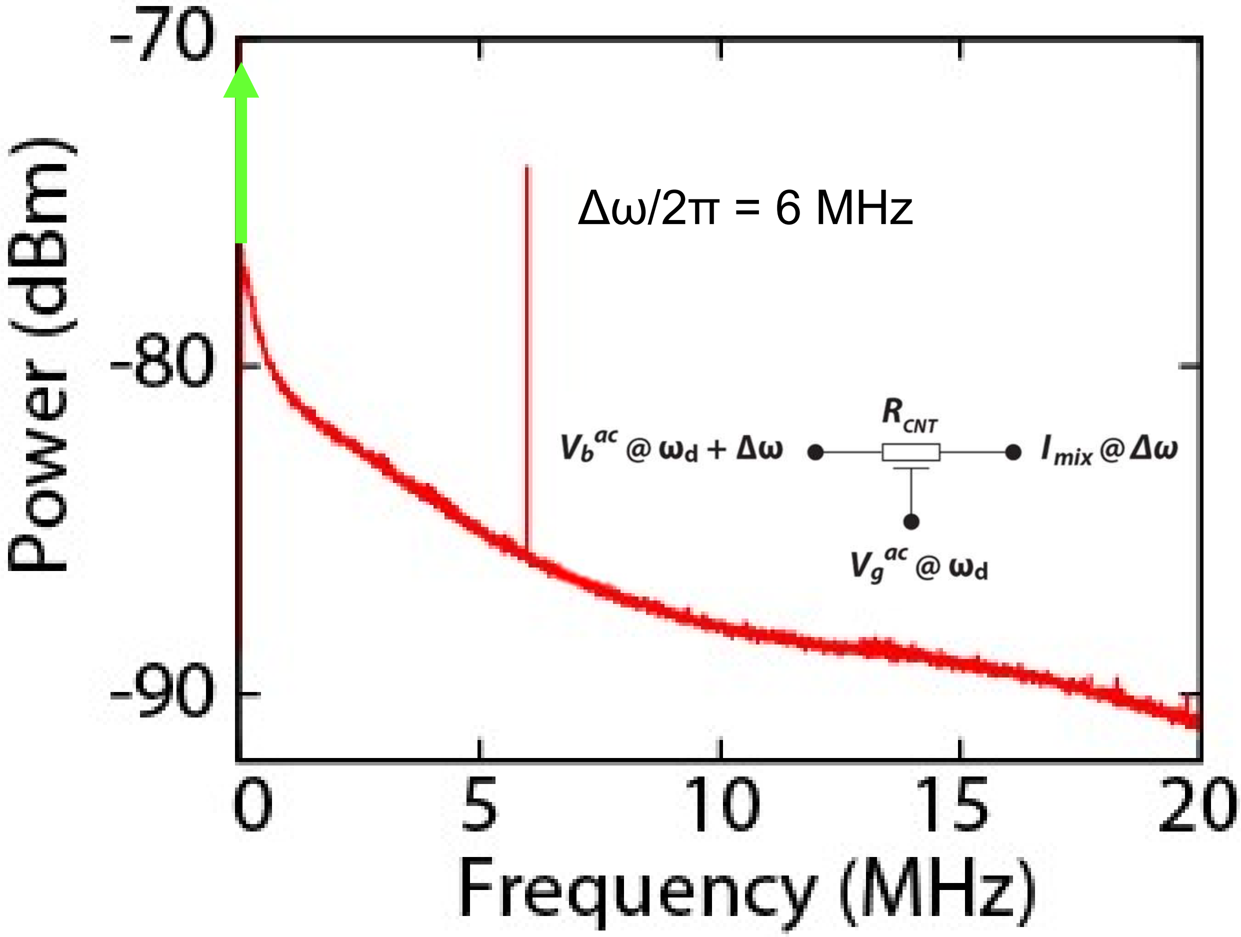




Amplifier characterization



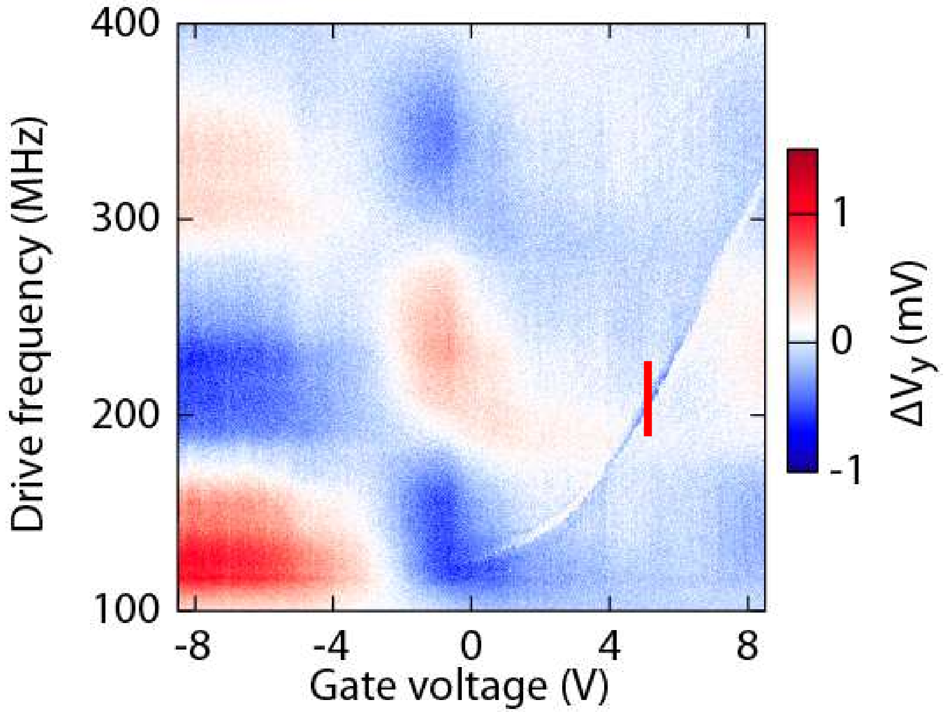
A CNT as a high-frequency mixer

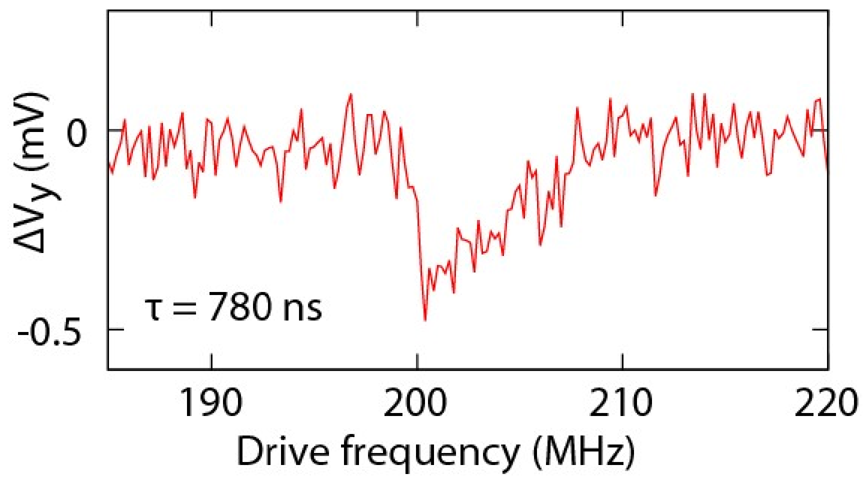


- Typically: intermediate frequency ~ 10 kHz

Sazonova et al.
Nature, 2004

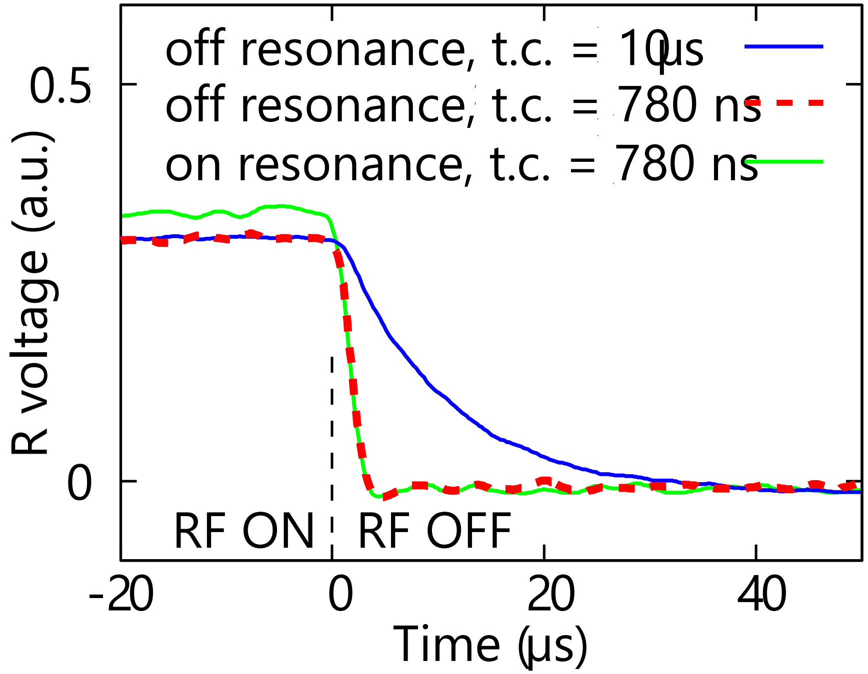
Fast readout of mechanical motion





- room-temperature vacuum
- timeconstant = 780 ns (typically: 100 ms)
- measurement time: 175 points × 780 ns ~ 0.1 ms!

Mixing signal in the time domain

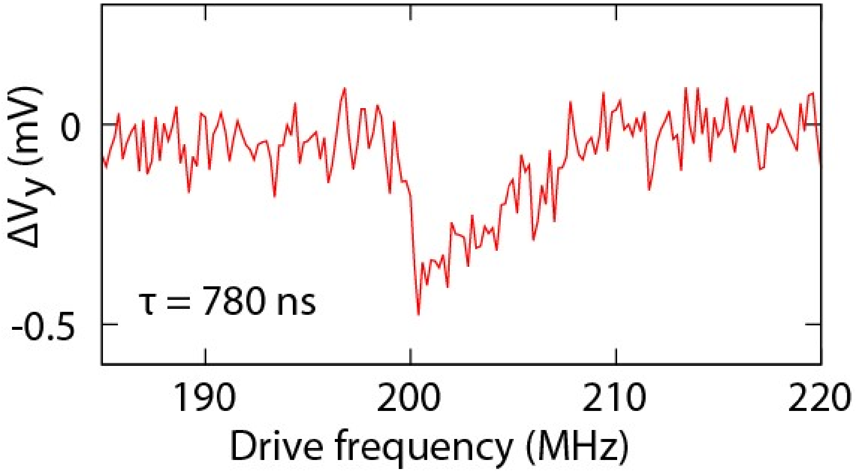


- decay time ~ time constant
- upper limit for $Q_{ringdown}$ < 490, at room temperature ($Q_{spectral}$ ~ 40)

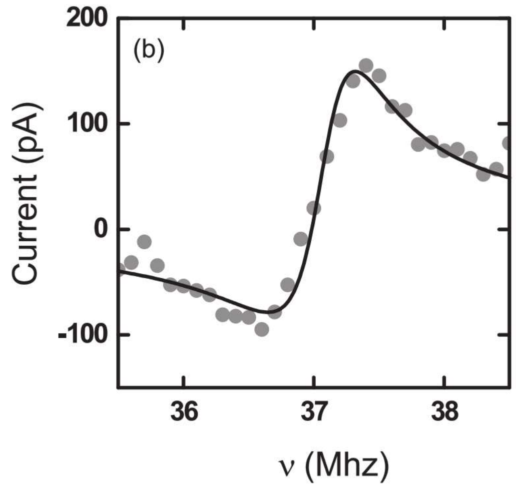
Conclusions

- We have used a close-proximity, high-impedance amplifier to measure a carbon nanotube resonator.
- We can measure five orders of magnitude faster than ever done, arriving at submicrosecond time resolution.
- We get an upper bound for room-temperature energy relaxation of $Q_{ringdown} < 490$.
- Next step: cryogenic measurements (higher Q)

Mechanical lineshape

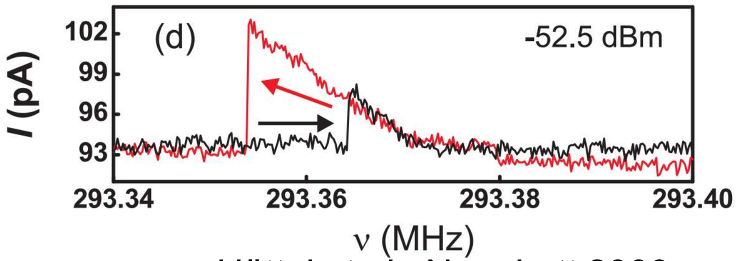


- Mixing → Fano lineshape



Witkamp et al., NanoLett 2006

- Strong driving → Nonlinear/Duffing lineshape

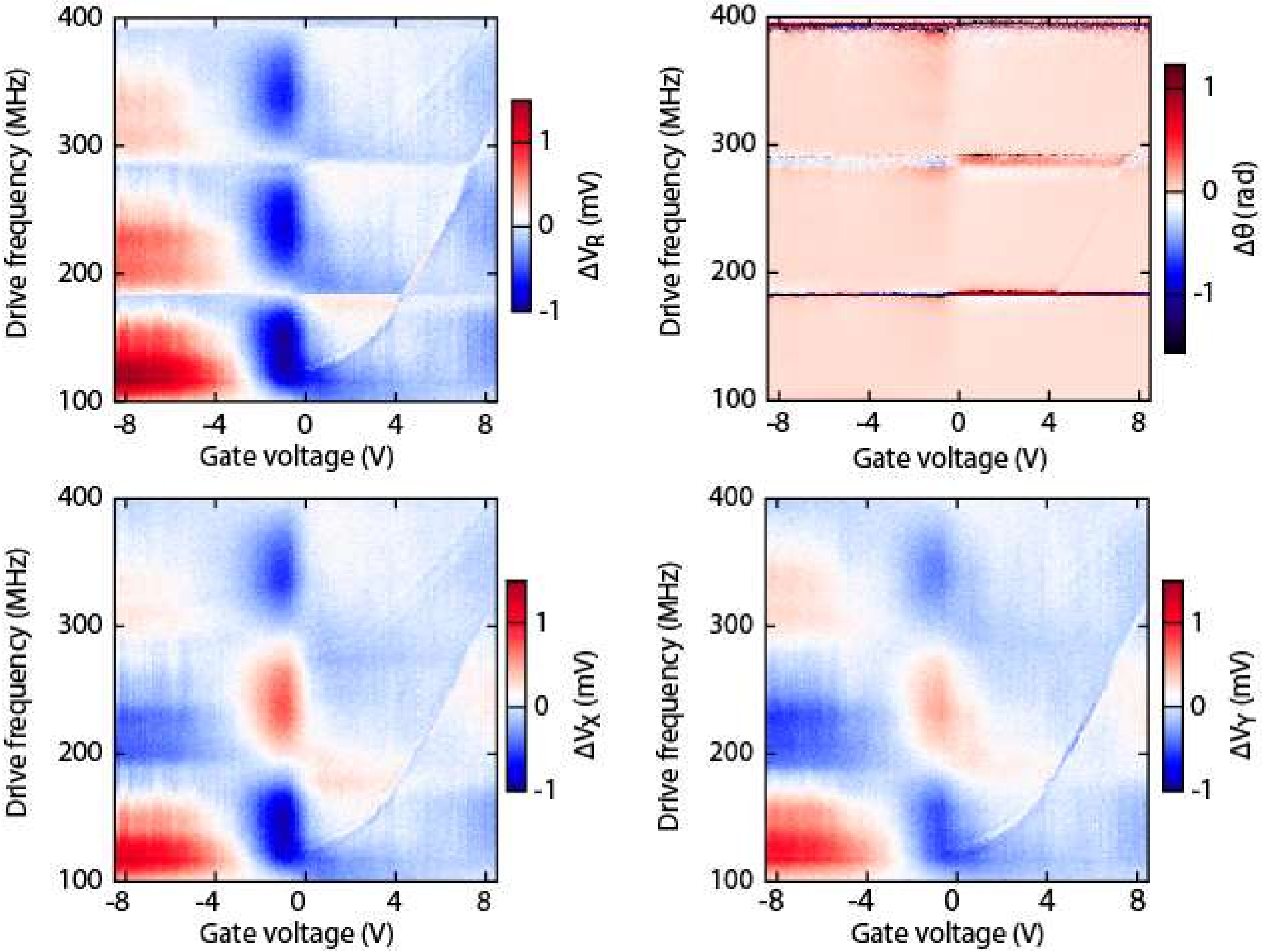


Hüttel et al., NanoLett 2009

Quadratures of lockin signal

R

phase



X

Y