Microwave optomechanics with a carbon nanotube

... and some news about MoS_2 too ...

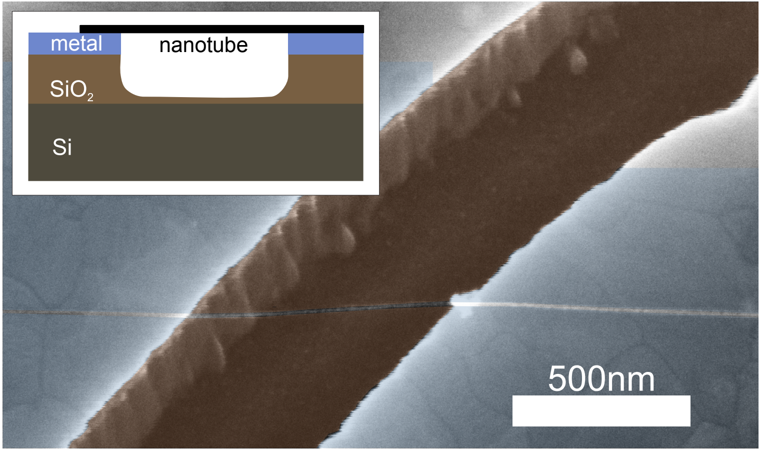
Andreas K. Hüttel

University of Regensburg

current affiliation: Aalto University, Espoo, Finland

IWEPNM 2020, Kirchberg in Tirol, 13 March 2020

suspended carbon nanotubes: NEMS and quantum transport

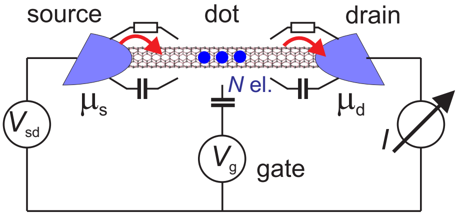


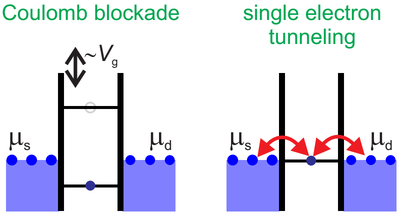
D. R. Schmid *et al.*, PRB **91**, 155439 (2015), K. J. G. Götz *et al.*, PRL **120**, 246802 (2018), M. Margańska *et al.*, PRL **122**, 086802 (2019)

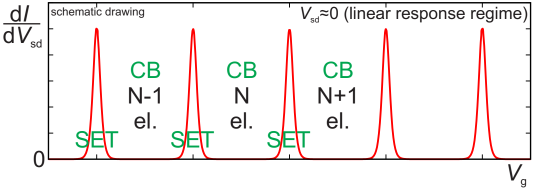
low-temperature transport: Coulomb blockade

tunnel barriers between contacts and nanotube; low temperature $k_B T \ll e^2/C$: quantum dot

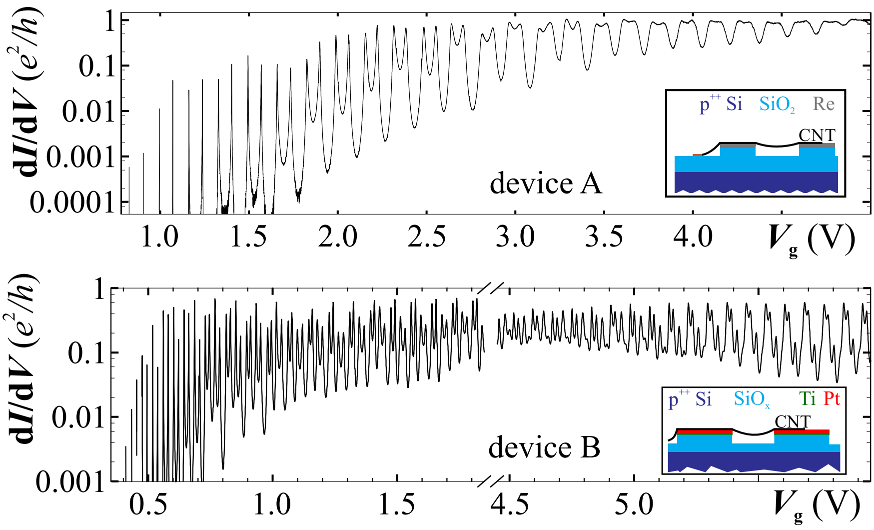
all following measurements at $T_{base} \lesssim 10\,\mathrm{mK}$ (unless noted)





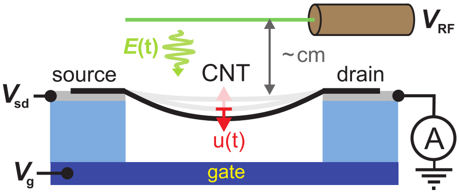


clean transport spectrum, shell effects

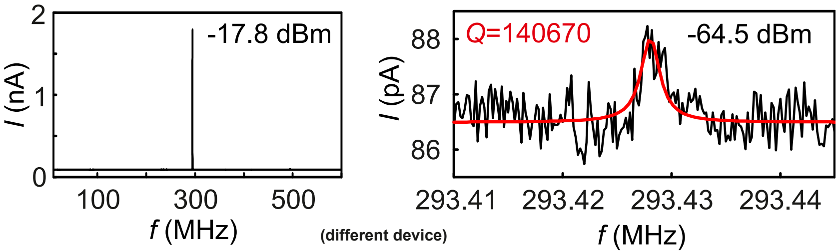


K. J. G. Götz *et al.*, PRL **120**, 246802 (2018)

driven transversal vibrations, "the old-fashioned way"

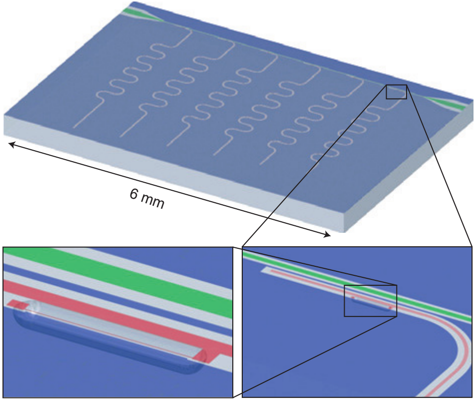


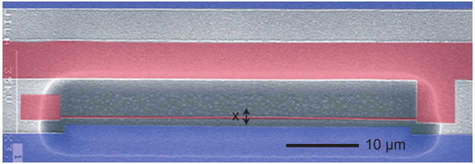
- transport spectroscopy setup plus rf irradiation
- mechanical resonance visible in time-averaged current



A. K. Hüttel *et al.*, Nano Lett. **9**, 2547 (2009)

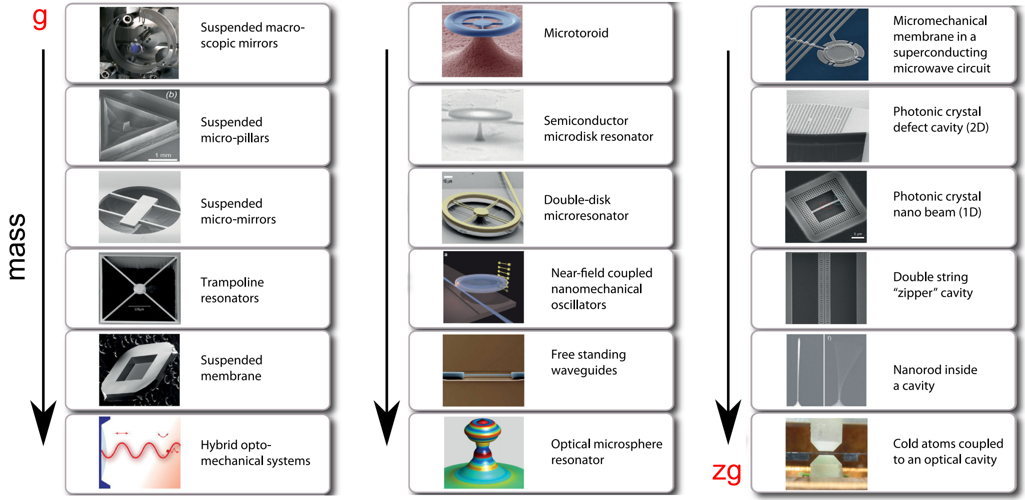
how about doing microwave optomechanics with a nanotube?





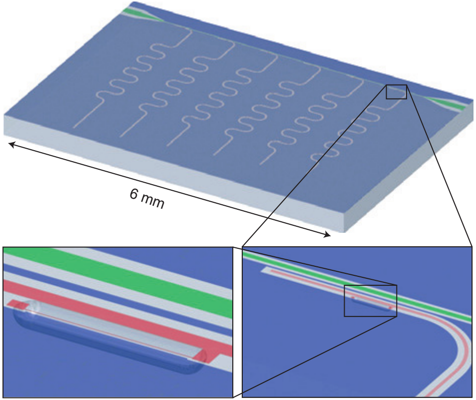
C. A. Regal *et al.*,
Nature Physics **4**, 555 (2008)

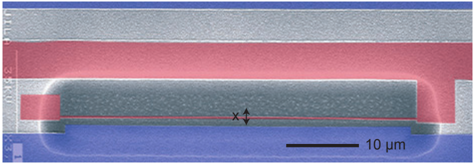
highly active field of research



M. Aspelmeyer et al., Rev. Mod. Phys. **86**, 1391 (2014)

how about doing microwave optomechanics with a nanotube?

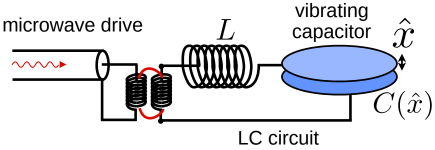


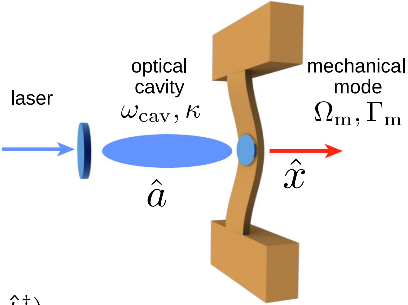


C. A. Regal *et al.*,
Nature Physics **4**, 555 (2008)

dispersive optomechanical coupling

moving element modulates CPW resonator capacitance $\leftrightarrow$ optical cavity with moving mirror





$$\hat{H}_{\mathrm{int}} = -\hbar g_0\, \hat{a}^\dagger \hat{a} \left(\hat{b} + \hat{b}^\dagger\right)$$

$$g_0 = \left.\frac{\partial \omega_{\mathrm{cav}}}{\partial x}\right|_{x=0} x_{\mathrm{zpf}} = \frac{\omega_{\mathrm{cav}}}{2C_{\mathrm{cav}}} \left.\frac{\partial C_{\mathrm{cav}}}{\partial x}\right|_{x=0} x_{\mathrm{zpf}}$$

M. Aspelmeyer et al., Rev. Mod. Phys. **86**, 1391 (2014)

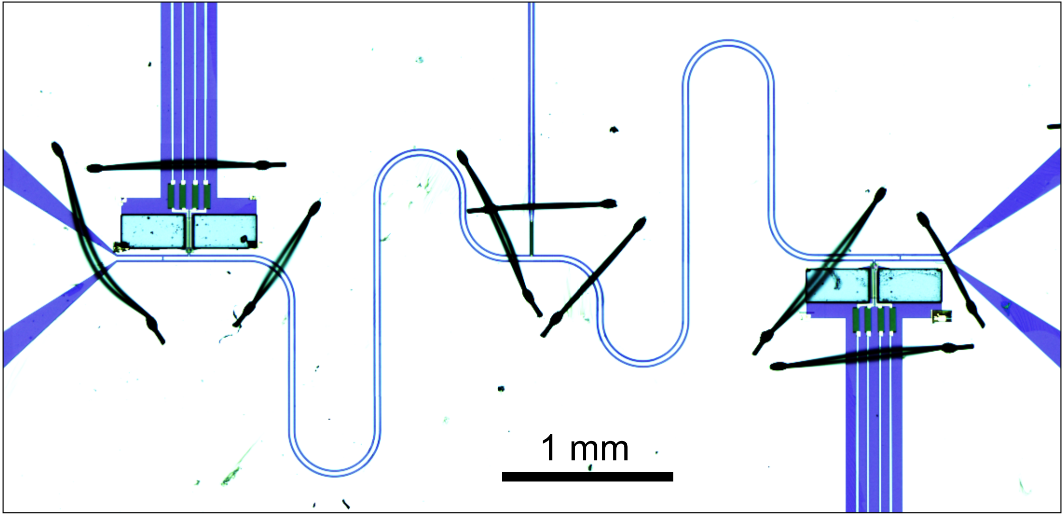
numbers for dispersive coupling?

		carbon nanotube	graphene drum V. Singh *et al.* (2014)	aluminum beam C. A. Regal *et al.* (2008)
mass	m	10^{-20} kg		2×10^{-15} kg
resonance frequency	f_{mech}	503 MHz	36 MHz	2.3 MHz
quality factor	Q_{mech}	10^4	10^5	10^5
zero point fluct.	x_{zpf}	2 pm	30 fm	40 fm
cavity frequency	f_{cav}	5.7 GHz	5.9 GHz	5 GHz
cavity Q	Q_{cav}	437	25000	10000
cavity occupation	n_{cav}	6.75×10^4	(6.75×10^4)	(6.75×10^4)
coupling capacitance	C_g	2.6 aF	580 aF	
capacitance sensitivity	$\partial C_g / \partial x$	1 pF/m		170 pF/m
zero-photon coupling	g_0	2.9 mHz	0.83 Hz	0.15 Hz
dispersive coupling	$g_0 Q_{cav} / f_{cav}$	2×10^{-10}	3×10^{-6}	3×10^{-7}
sideband cooling rate	$\kappa_{opt} (\propto n_{cav})$	$\sim 10^{-7}$ Hz	0.77 Hz	12 mHz

A single-wall carbon nanotube is a great mechanical resonator, but is also annoyingly small.

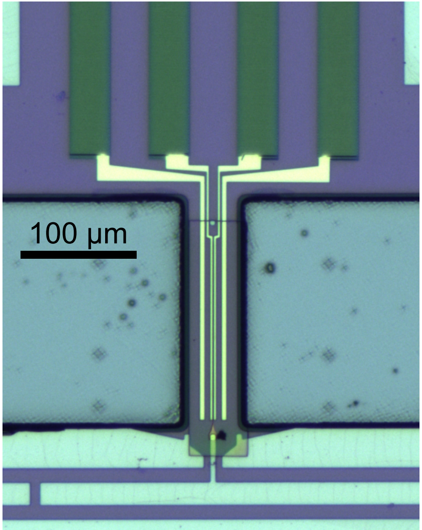
S. Blien *et al.*, Nature Comm. **11**, 1636 (2020); V. Singh *et al.*, Nat. Nano **9**, 820 (2014); C. A. Regal *et al.*, Nat. Phys. **4**, 555 (2008)

we built it anyway (geometry is not everything!)



S. Blien *et al.*, Nature Comm. **11**, 1636 (2020)

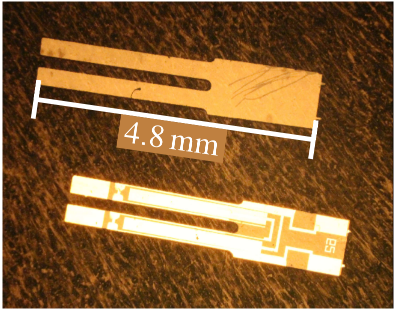
nanotube deposition area

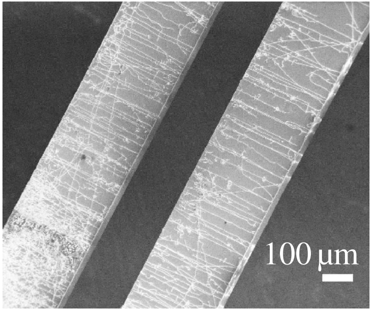


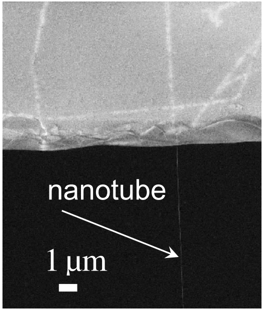
- gate finger connected to cavity
- isolation layer (cross-linked PMMA)
- long resistive meanders as RF block
- four gold electrodes
  (source, drain, and two for cutting)
- deep-etched areas to allow fork deposition

S. Blien *et al.*, Nature Comm. **11**, 1636 (2020)

nanotube growth on commercial quartz tuning forks



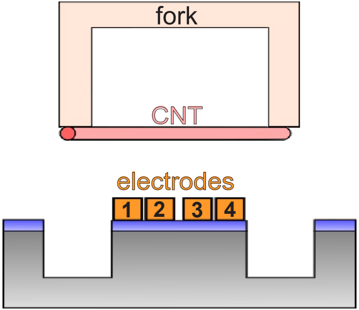


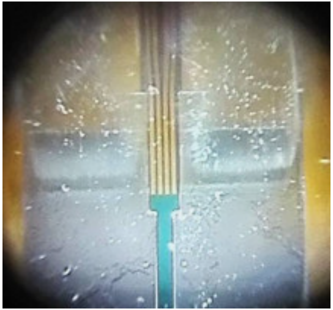


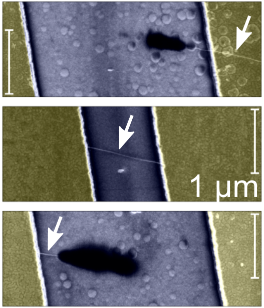
nominally 1nm Co sputter-deposited as catalyst; growth in high gas flow

details: S. Blien *et al.*, PSSb **255**, 1800118 (2018)

nanotube deposition



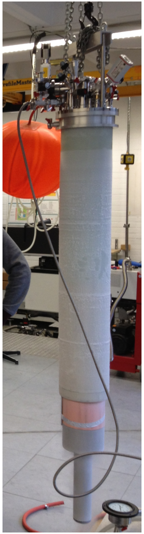


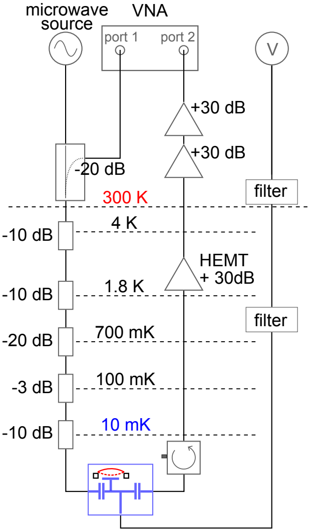


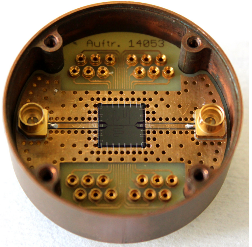
lower fork, detect contact electrically, burn outer segments with current, retract fork

details: S. Blien *et al.*, PSSb **255**, 1800118 (2018)

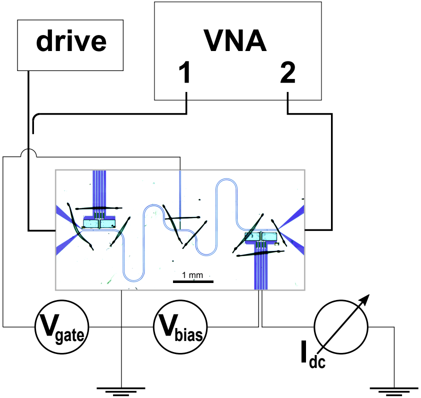
now this is cooled to 10mK

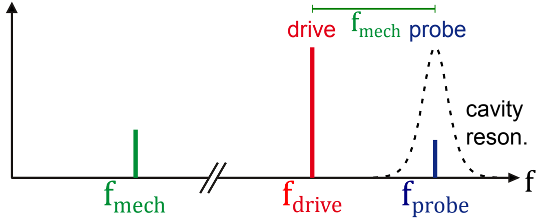






optomechanically induced (in)transparency (I)

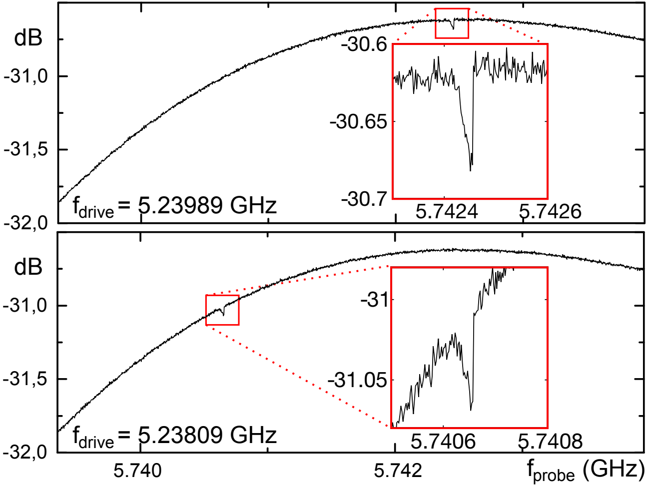




- strong drive at $f_{drive} = f_{cav} - f_{mech}$ (red sideband)
- probe transmission with weak signal f_{probe} near f_{cav}
- when $f_{probe} - f_{drive} = f_{mech}$:
  interaction with mechanics $\longrightarrow$ signal loss

S. Blien *et al.*, Nature Comm. **11**, 1636 (2020)

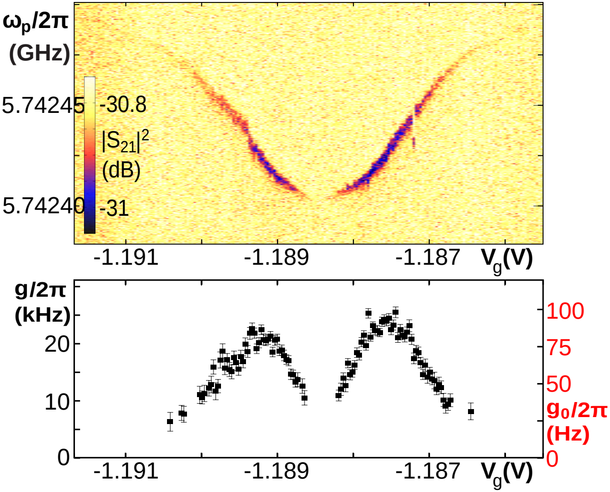
optomechanically induced (in)transparency (II)



- clear OMIT feature for $f_{\mathrm{probe}} - f_{\mathrm{drive}} = f_{\mathrm{mech}}$
- **in**transparency due to specific cavity / detection arrangement
- would not be visible with $g_0 \sim 10\,\mathrm{mHz}$ (even at high drive power)
- obviously something was missing in the theory

S. Blien *et al.*, Nature Comm. **11**, 1636 (2020)

optomechanically induced (in)transparency (III) – now with gate!



- we trace the OMIT signal over a sharp CB oscillation
- "dip" position $\leftrightarrow$ $f_{\text{mech}}(V_g)$
- depth, width of "dip" $\leftrightarrow$ optomechanical coupling g
- fit each trace, extract $g(V_g)$
- large on flanks of SET peak $g \simeq 20\,\text{kHz}$ $g_0 = g/\sqrt{n_{\text{cav}}} \simeq 95\,\text{Hz}$
- in Coulomb blockade & at degeneracy point zero / no signal

S. Blien *et al.*, Nature Comm. **11**, 1636 (2020)

another type of capacitance

- Capacitance “seen” by the coplanar resonator:

$$C_{\mathrm{CNT}} = e\frac{\partial \langle Q_g \rangle}{\partial V_g} = \cdots = e\frac{C_g}{C_\Sigma}\frac{\partial \langle N \rangle}{\partial V_g} + \text{const.}$$

- The nanotube moves $\longrightarrow$ C_g changes by δC_g $\longrightarrow$ the Coulomb oscillations shift in V_g
- We define an *effective gate voltage modulation* equivalent to the motion:

$$C_g\,\delta V_g^{\mathrm{eff}} = V_{\mathrm{g}}\,\delta C_g$$

- This results in

$$\frac{\partial C_{\mathrm{CNT}}}{\partial x} = \frac{\partial C_{\mathrm{CNT}}}{\partial V_g^{\mathrm{eff}}}\frac{\partial V_g^{\mathrm{eff}}}{\partial x} = \cdots = e\,\frac{\partial^2 \langle N \rangle}{\partial V_g^2}\,\frac{V_g}{C_\Sigma}\,\frac{\partial C_g}{\partial x}$$

amplification factor!

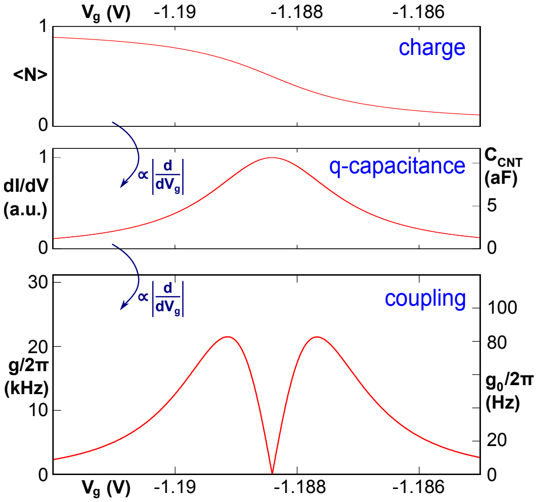
Coulomb blockade enhancement of coupling

$\langle N \rangle (V_g)$: tunneling through
Lorenz-broadened level, width Γ

$$\frac{\partial C_{\text{CNT}}}{\partial x} = e \frac{\partial^2 \langle N \rangle}{\partial V_g^2} \frac{V_g}{C_\Sigma} \frac{\partial C_g}{\partial x}$$

$$g_0 = \frac{\omega_{\text{cav}}}{2C_{\text{cav}}} \left. \frac{\partial C_{\text{CNT}}}{\partial x} \right|_{x=0} x_{\text{zpf}}$$

insert device values ...



S. Blien *et al.*, Nature Comm. **11**, 1636 (2020)

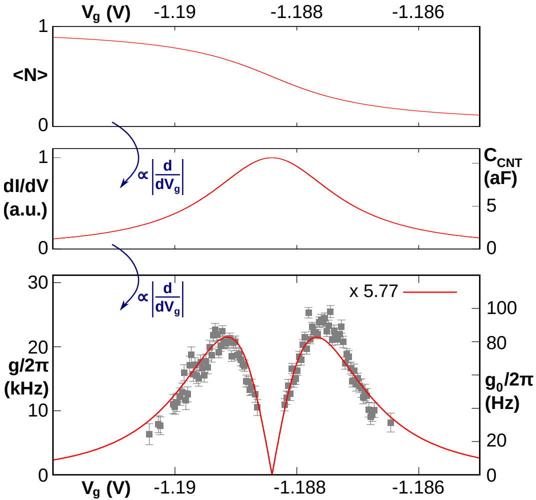
Coulomb blockade enhancement of coupling

$\langle N \rangle (V_g)$: tunneling through Lorenz-broadened level, width Γ

$$\frac{\partial C_{\mathrm{CNT}}}{\partial x} = e \frac{\partial^2 \langle N \rangle}{\partial V_g^2} \frac{V_g}{C_\Sigma} \frac{\partial C_g}{\partial x}$$

$$g_0 = \frac{\omega_{\mathrm{cav}}}{2C_{\mathrm{cav}}} \left. \frac{\partial C_{\mathrm{CNT}}}{\partial x} \right|_{x=0} x_{\mathrm{zpf}}$$

insert device values ...



S. Blien *et al.*, Nature Comm. **11**, 1636 (2020)

numbers for dispersive coupling?

		carbon nanotube	graphene drum V. Singh *et al.* (2014)	aluminum beam C. A. Regal *et al.* (2008)
mass	m	5×10^{-21} kg		2×10^{-15} kg
resonance frequency	f_{mech}	503 MHz	36 MHz	2.3 MHz
quality factor	Q_{mech}	10^4	10^5	10^5
zero point fluct.	x_{zpf}	2 pm	30 fm	40 fm
cavity frequency	f_{cav}	5.74 GHz	5.9 GHz	5 GHz
cavity Q	Q_{cav}	497	25000	10000
cavity occupation	n_{cav}	6.75×10^4	(6.75×10^4)	(6.75×10^4)
coupling capacitance	C_g	10 aF	580 aF	
zero-photon coupling	g_0	95 Hz	0.83 Hz	0.15 Hz
dispersive coupling	$g_0 Q_{cav} / f_{cav}$	8×10^{-6}	3×10^{-6}	3×10^{-7}
sideb. cooling rate	$\kappa_{opt} (\propto n_{cav})$	211 Hz	0.77 Hz	12 mHz

Suddenly this is much more interesting (even for our low n_{cav} and Q_{cav}).

S. Blien *et al.*, Nature Comm. **11**, 1636 (2020); V. Singh *et al.*, Nat. Nano **9**, 820 (2014); C. A. Regal *et al.*, Nat. Phys. **4**, 555 (2008)

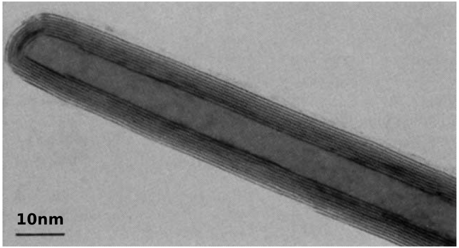
outlook

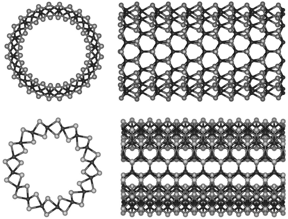
- first optomechanical system with electronic quantum confinement
- improve coplanar cavity parameters, coupling, amplification
  - re-arrange attenuators, better HEMT amplifier, insert a JPA
  - simulate and optimize cavity geometry
  - improve dc cable filtering
  - ...
- $g \gtrsim \kappa_m, \kappa_{cav}$ reachable, $C \sim n_{th}$ reachable $\longrightarrow$ quantum control of motion!
- good cavity limit: cooling, heating, temperature readout, energy balance with single electron tunneling!
  (note that $k_B T_{base} \lesssim h f_{mech}$)
- bad cavity limit: conductance measurement with $\gtrsim$ 100 MHz bandwidth
- quantum state transfer, mechanical quantum information processing ... and much more ...

And now for something completely different.

And now for something completely different.

let's go TMDC!

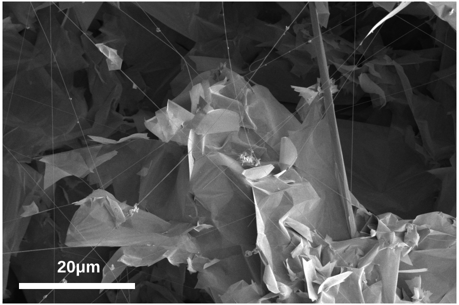


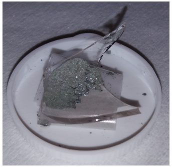


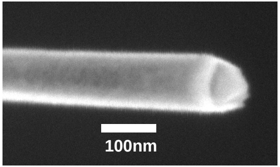
- first synthesis of WS_2 and MoS_2 multiwall nanotubes in 1992 by R. Tenne
- all chiralities semiconducting
- band gap decreases with radius
- intrinsic superconductivity, e.g., in WS_2 nanotubes via ionic gating: F. Qin *et al.*, Nat. Comm. **8**, 14465 (2017) F. Qin *et al.*, Nano Letters **18**, 6789 (2018)
- we get spatial confinement for free!
- no previous work on quantum dots and low temperature transport spectroscopy

R. Tenne *et al.*, Nature **360**, 444 (1992); G. Seifert *et al.*, PRL **85**, 146 (2000)

TMDC nanotube growth (group M. Remškar, Ljubljana)







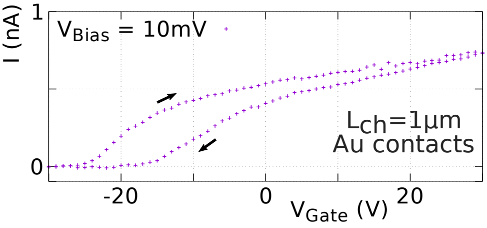
- two-zone furnace
- iodine-assisted chemical transport reaction
  M. Remškar *et al.*, APL **69**, 351 (1996)

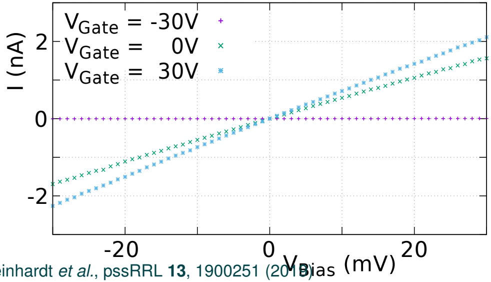
- slow, near-equilibrium growth
- near defect-free nanostructures

- mixture of 2d and 1d morphologies
- individual multiwall tubes
- diameter from $\sim$ 10 nm up to several µm
- length up to several millimeters

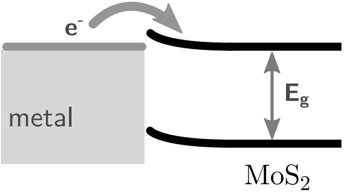
S. Reinhardt *et al.*, pssRRL **13**, 1900251 (2019)

MoS_2 nanotube device, $T = 300\,K$



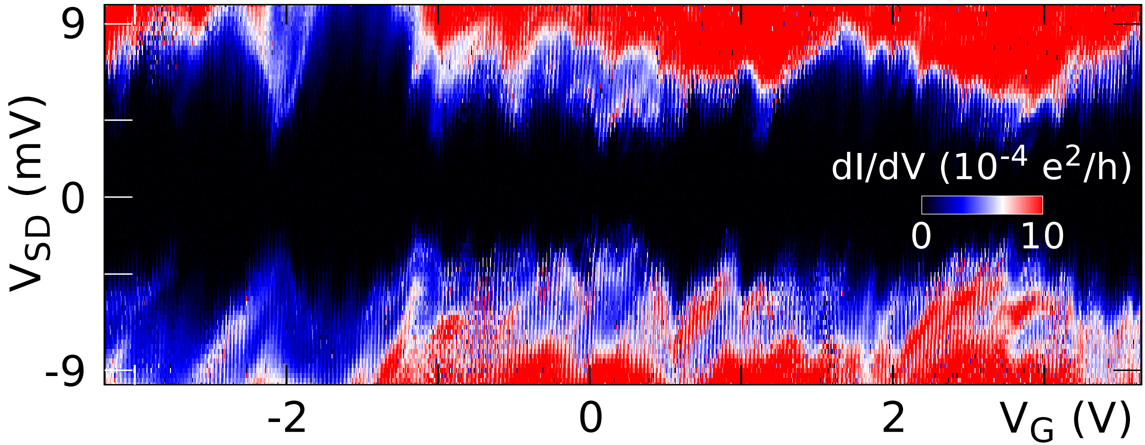


- n-type field effect
- linear $I(V)$ characteristics
- $R_{on} \approx 15\,M\Omega$
- Fermi-level pinning to conduction band
- not perfect yet, but promising



S. Reinhardt *et al.*, pssRRL **13**, 1900251 (2019)

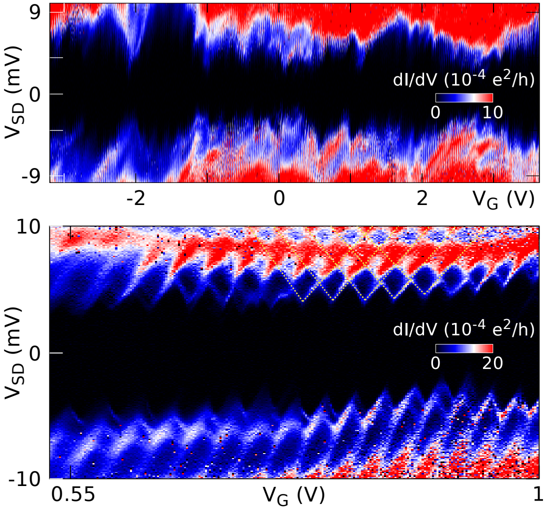
stability diagram, $T = 0.3\,\mathrm{K}$ (1)

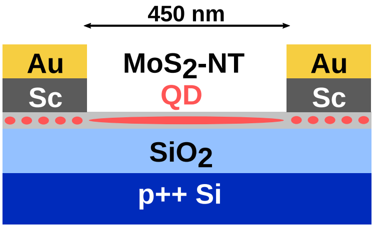


doesn't look that nice yet, but...

S. Reinhardt *et al.*, pssRRL **13**, 1900251 (2019)

stability diagram, $T = 0.3\,\mathrm{K}$ (2)



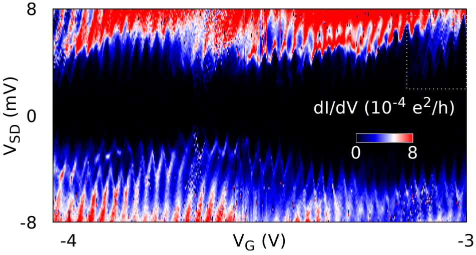


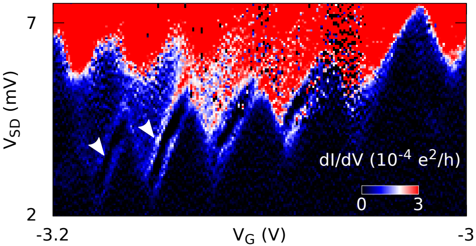
- large scale: disordered system of quantum dots
- zoom: highly regular Coulomb oscillations
- trap states at the metal contacts!

  capacitances confirm this

S. Reinhardt *et al.*, pssRRL **13**, 1900251 (2019)

excitation lines!





- excitation lines visible in conductance, $\Delta E \sim 500\,\mu\text{eV}$
- expected mean level spacing for a chaotic quantum dot (assuming $r = 10\,\text{nm}$, $l = 450\,\text{nm}$):

$$\Delta E = \frac{\hbar^2 \pi}{m^* A} \sim 10\,\mu\text{eV}$$

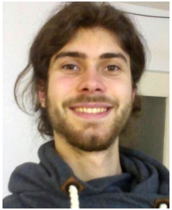
- 1D geometry, large $N_{el} \longrightarrow$ large ΔE?
- band structure calculations and 2d magnetotransport data exist
- no theory on confinement spectrum yet
- many more measurements needed

S. Reinhardt *et al.*, pssRRL **13**, 1900251 (2019)

thanks

Stefan Blien

Patrick Steger

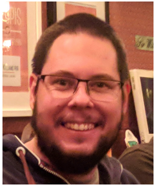


Niklas Hüttner

Richard Graaf

Simon Reinhardt

Christian Bäuml



Luka Pirker

Prof. Maja Remškar

Thomas Huber
Dr. Ondrej Vavra
Dr. Andreas Pfeffer

Prof. Dieter Weiss
Prof. Christoph Strunk

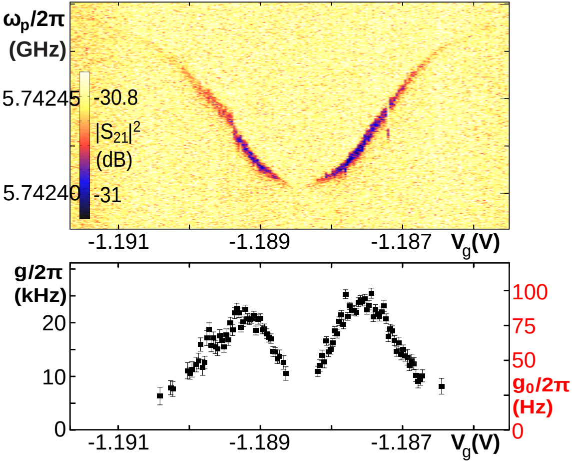
Prof. Eva Weig

Prof. Florian Marquardt
Prof. Yaroslav Blanter

Prof. Pertti Hakonen

... and many others

thank you! — questions?



Microwave optomechanics: S. Blien *et al.*, Nature Comm. **11**, 1636 (2020)

MoS_2 nanotubes: S. Reinhardt *et al.*, pssRRL **13**, 1900251 (2019)