Strong Coupling of Single Electron Tunneling to Nanomechanical Motion in Clean Carbon Nanotubes

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Outline

I. Introduction: Clean carbon nanotubes

- What is a clean carbon nanotube?
- Quantum dots in clean nanotubes: Klein Tunnelling

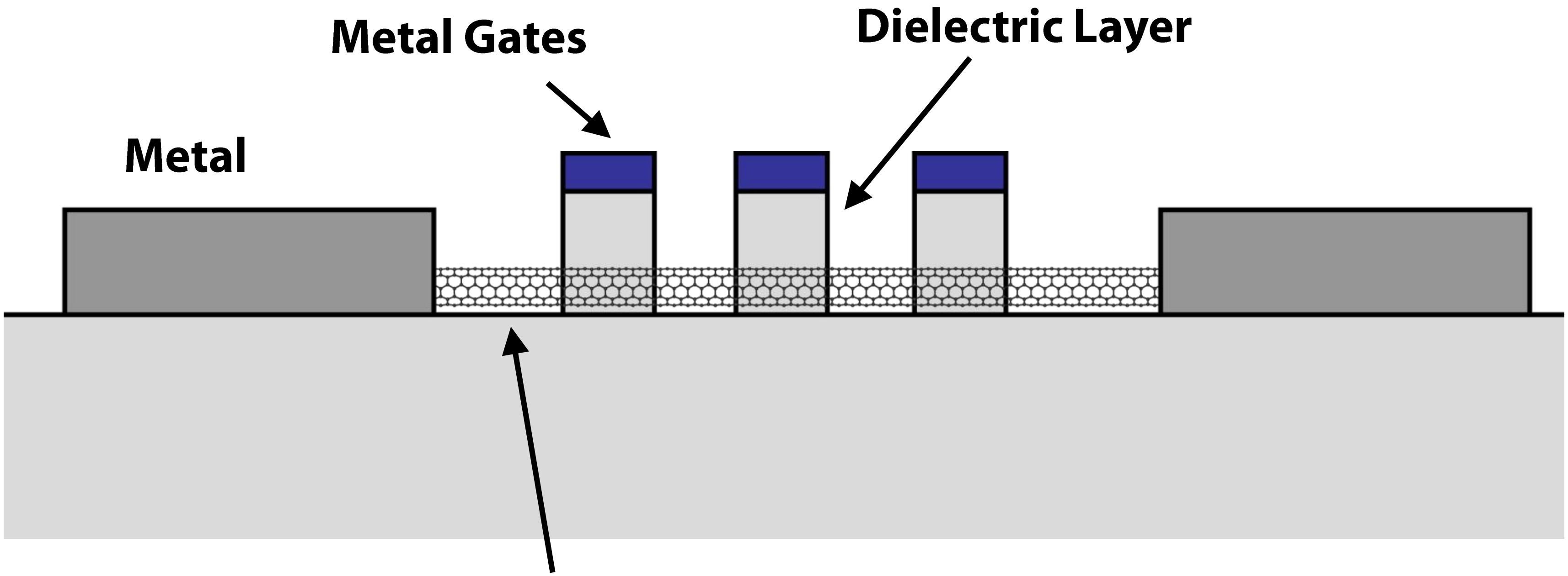
II. Nanomechanics

- High quality mechanical resonators
- Coupling single electrons to nanomechanical motion
- The Future: Quantum Nanomechanics?

Clean Carbon Nanotubes

What is a "clean" carbon nanotube?

Conventional Nanotube Device



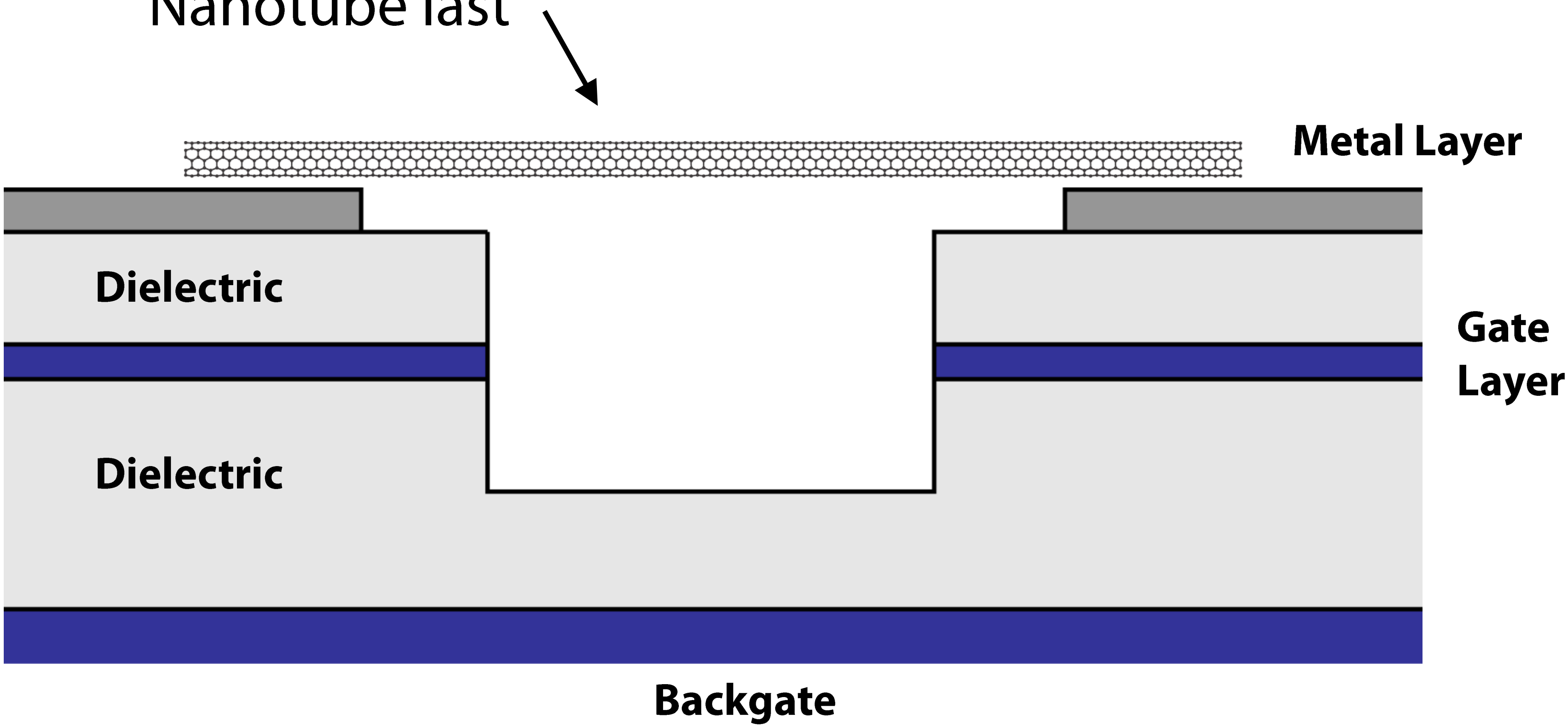
Nanotube first

What is a "clean" carbon nanotube?

"Clean" nanotube device

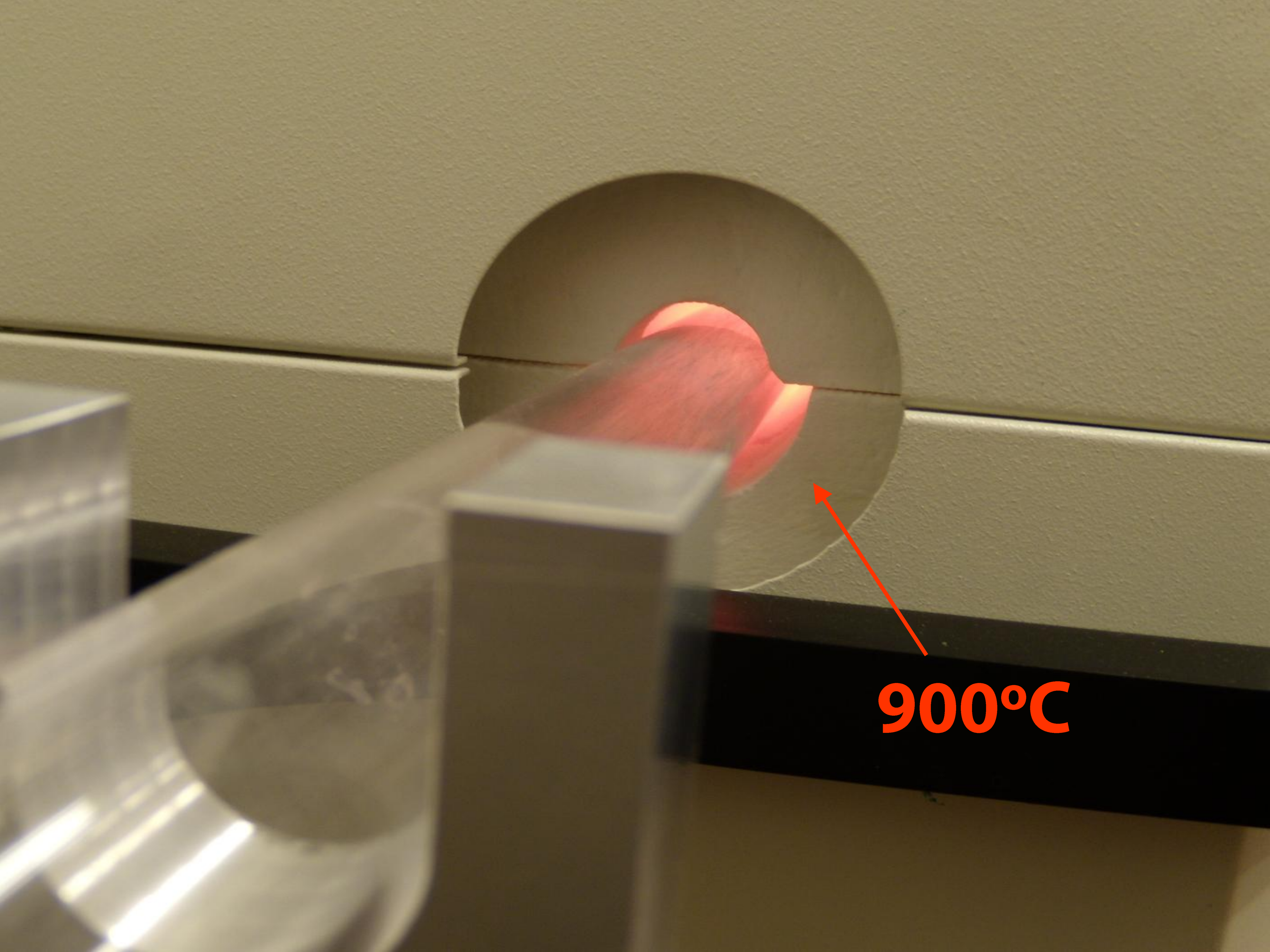
"flip device upside down"

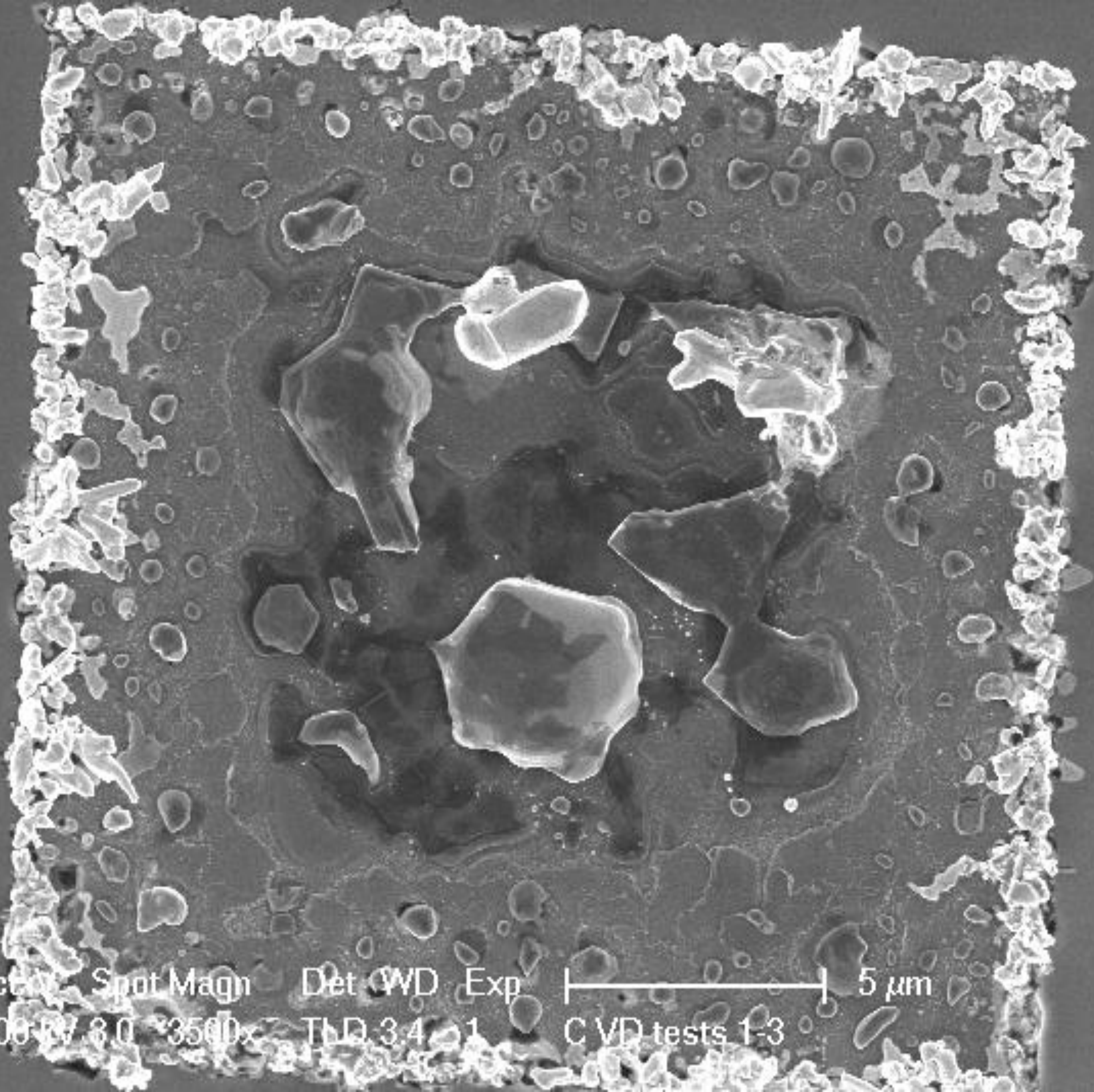
Nanotube last



Nanotube growth …

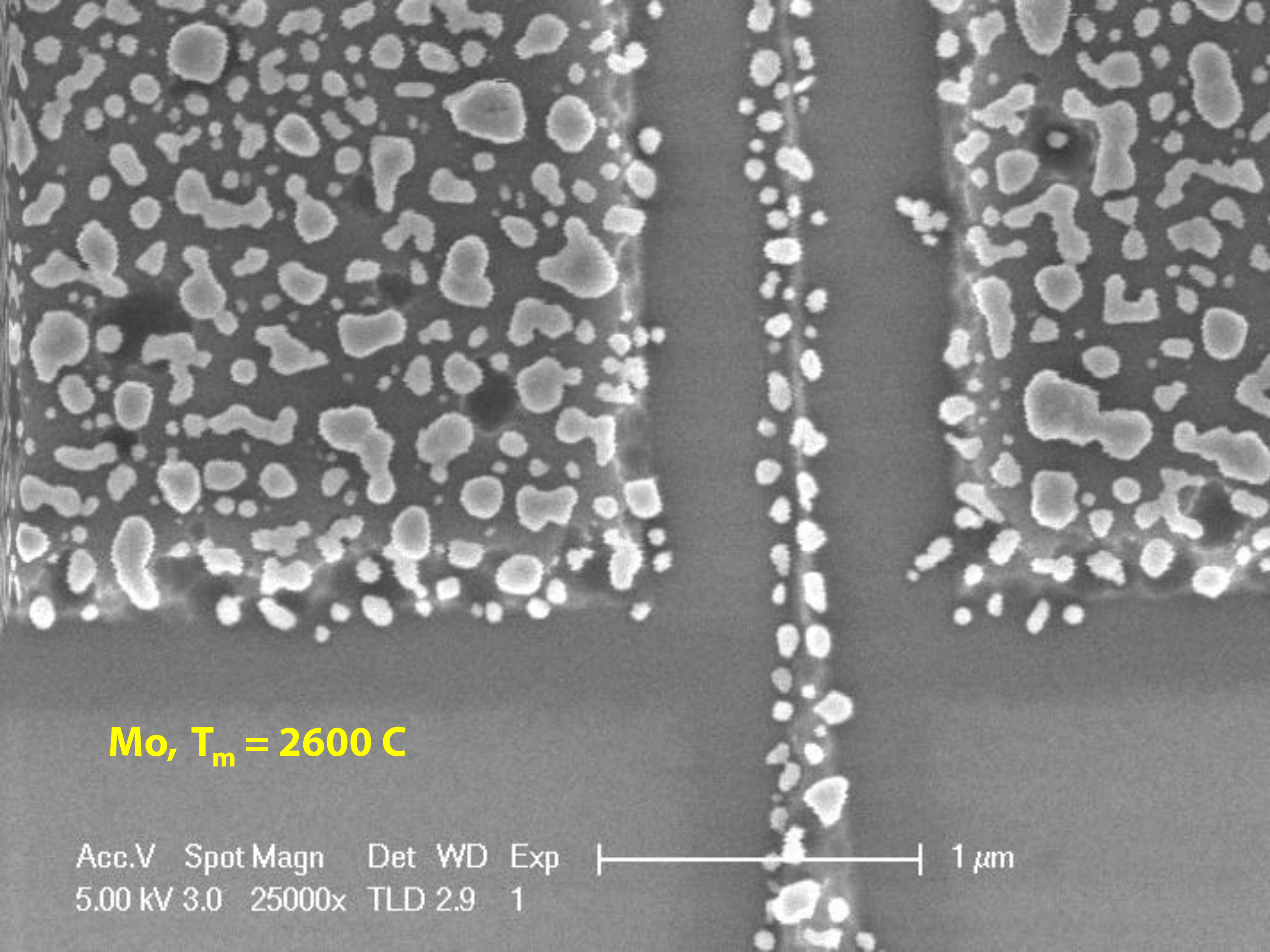
$CH_4 + H_2$ →

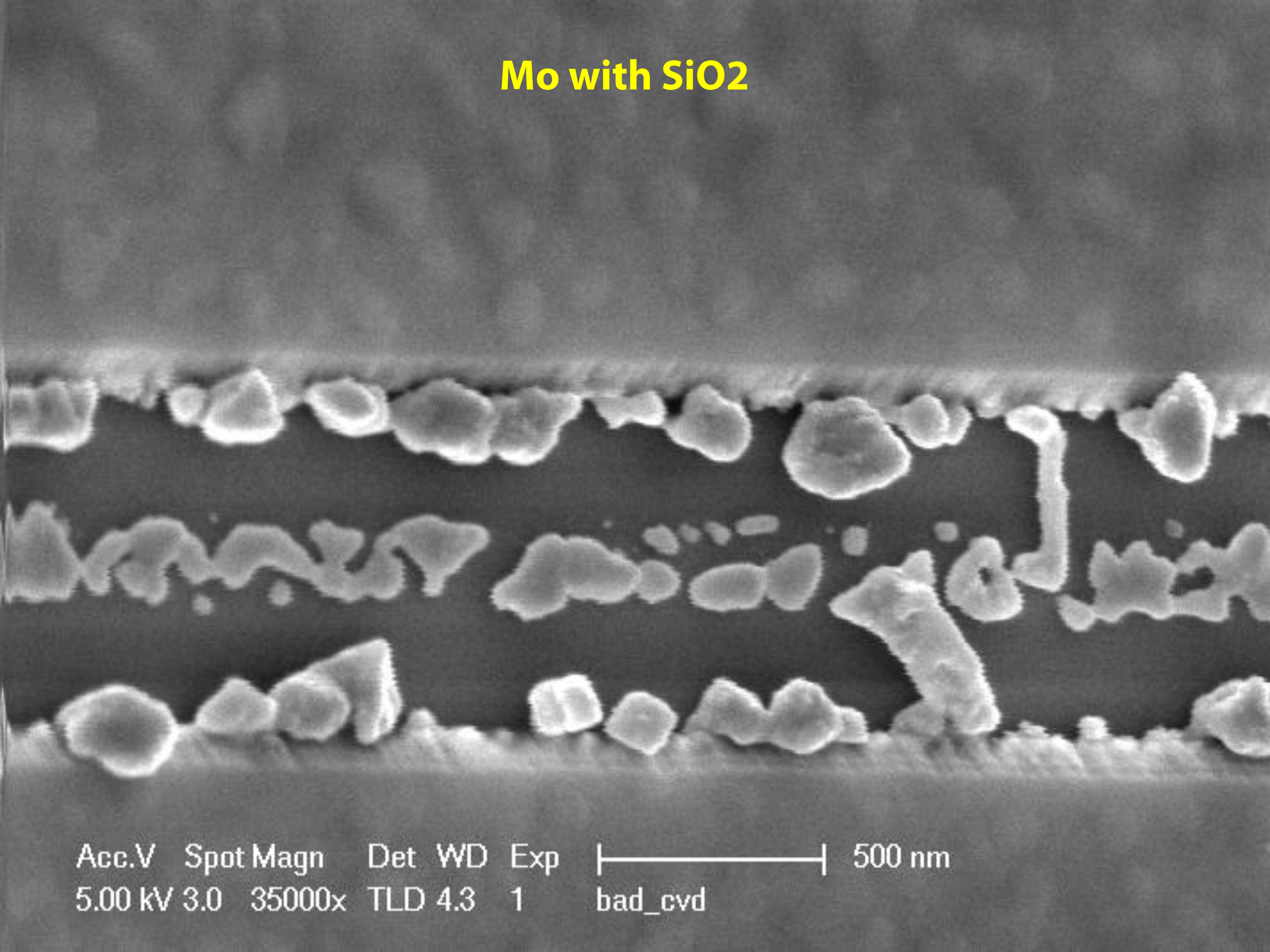

900°C

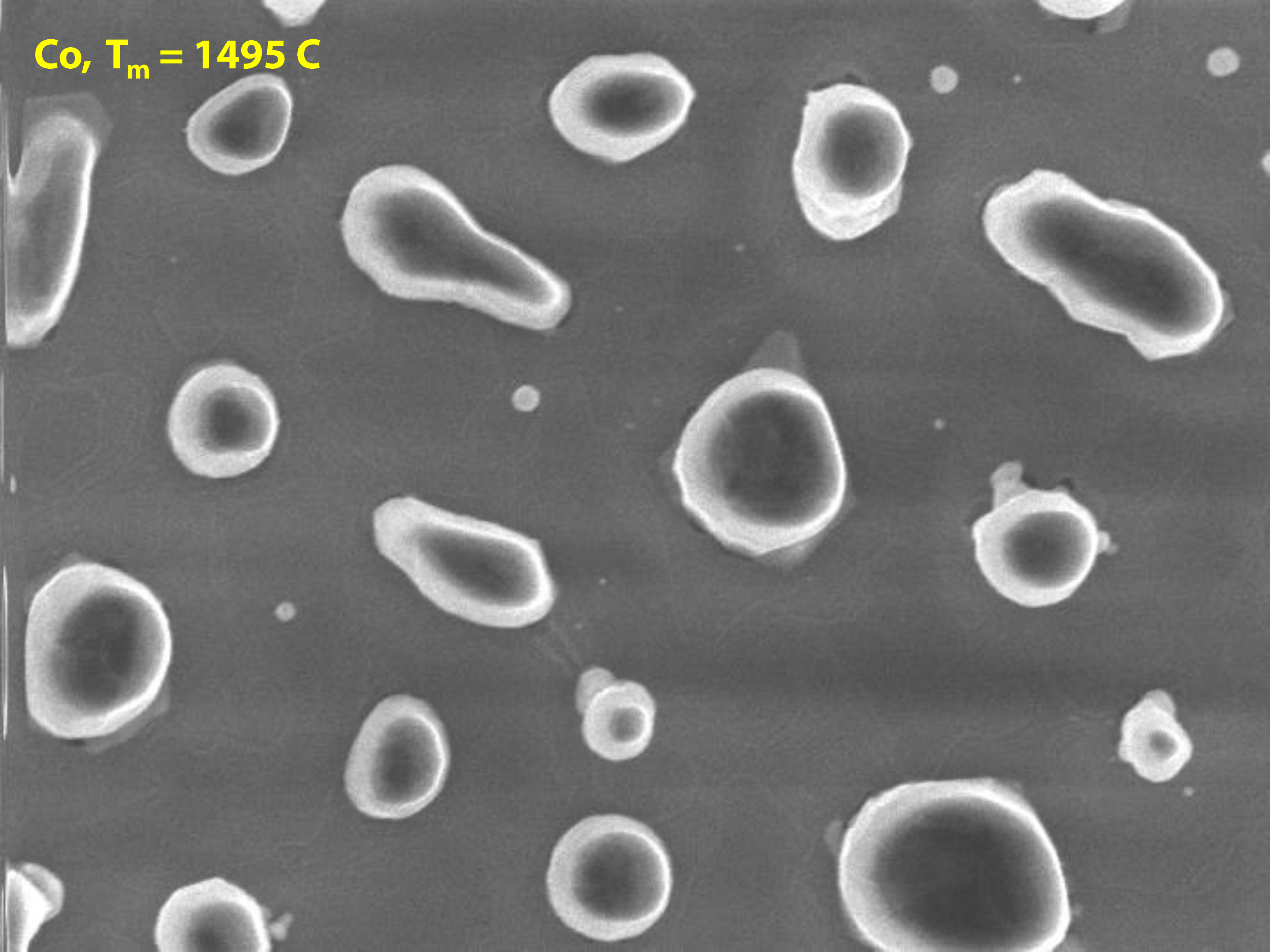


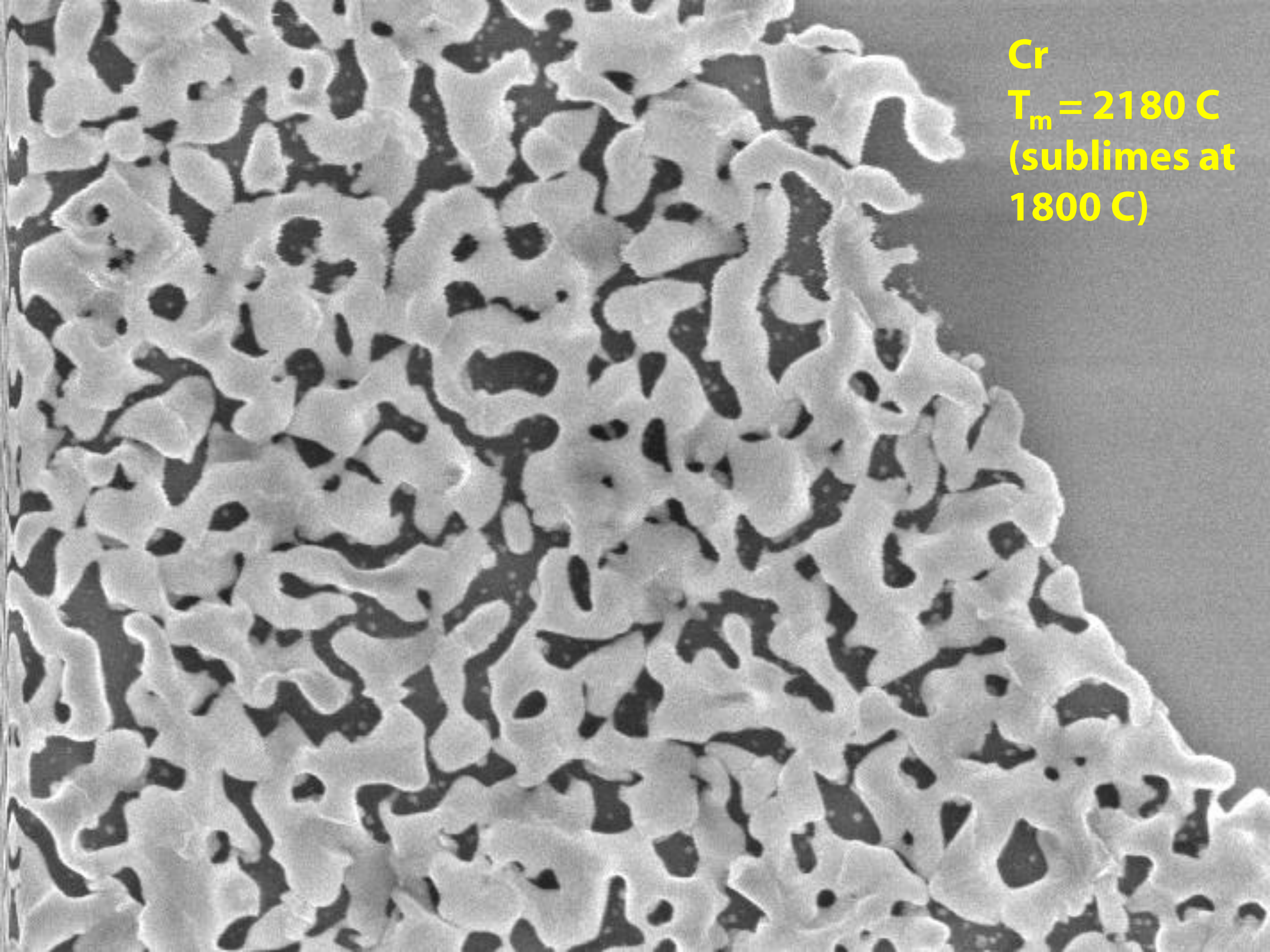
Ti/Pt,

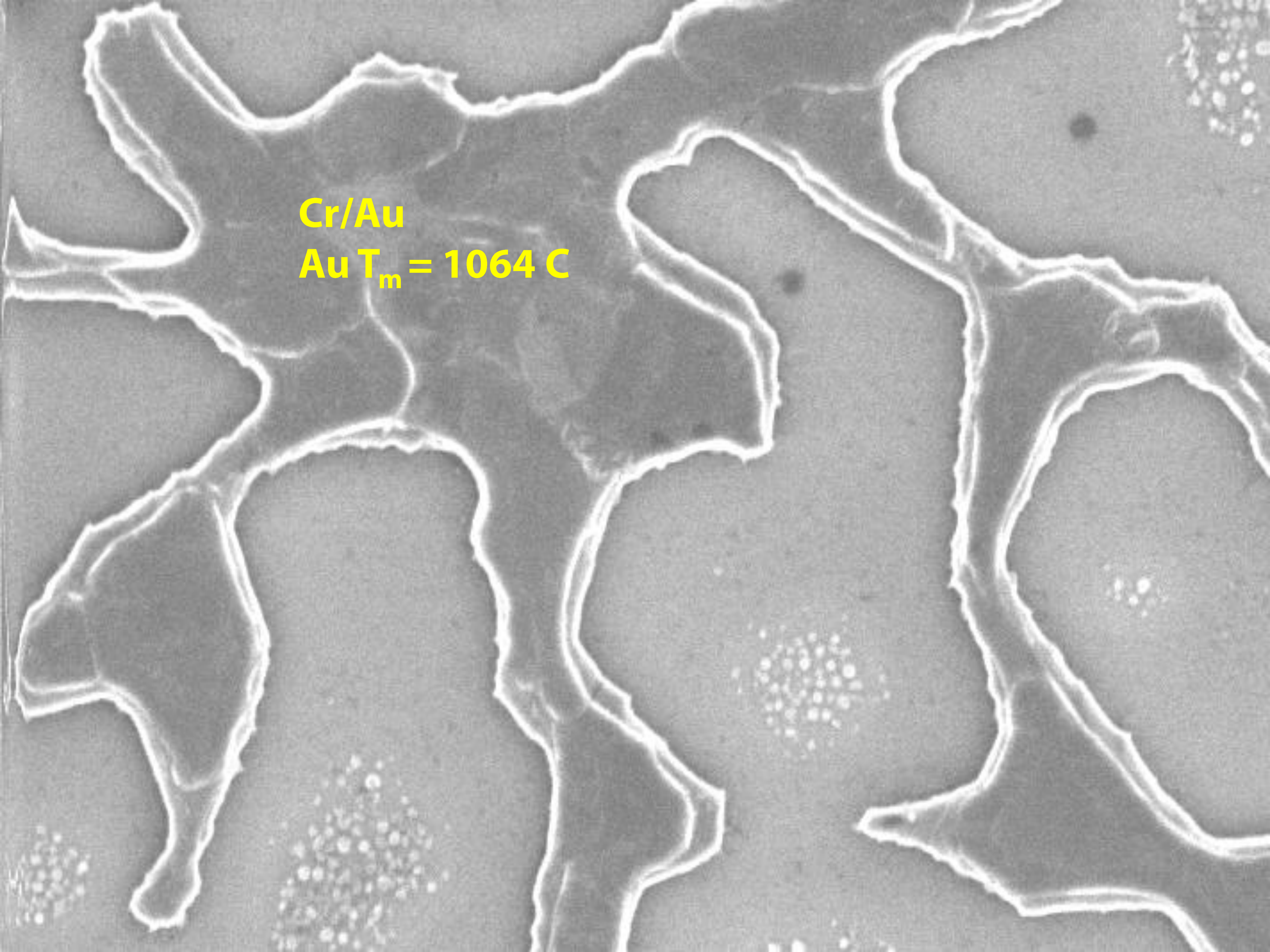
Pt T_m = 1700 C

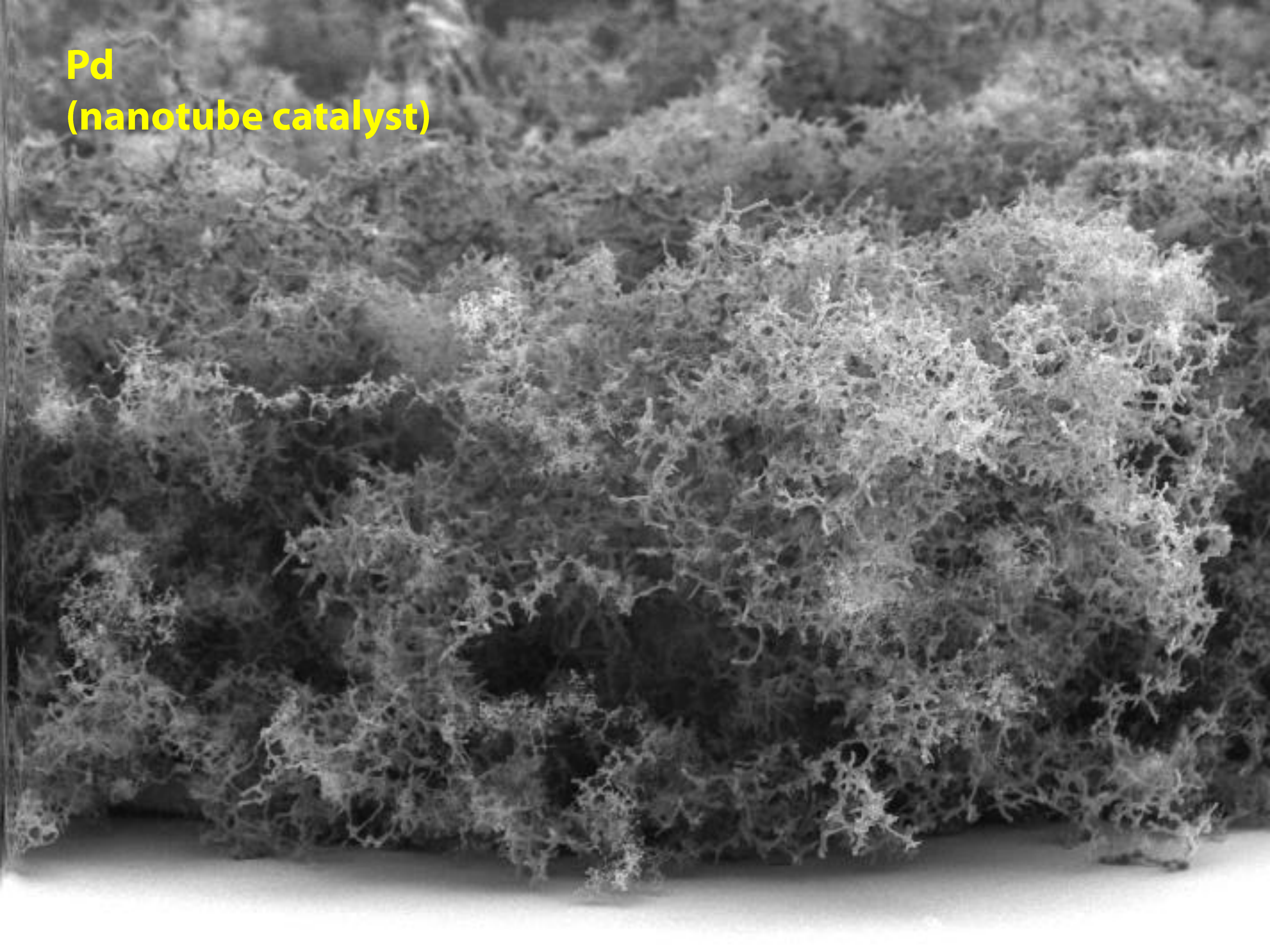

Mo, T_m = 2600 C
Acc.V Spot Magn Det WD Exp
5.00 kV 3.0 25000x TLD 2.9 1
1 μm


Mo with SiO2
Acc.V Spot Magn Det WD Exp
5.00 kV 3.0 35000x TLD 4.3 1
500 nm
bad_cvd


Co, T_m = 1495 C

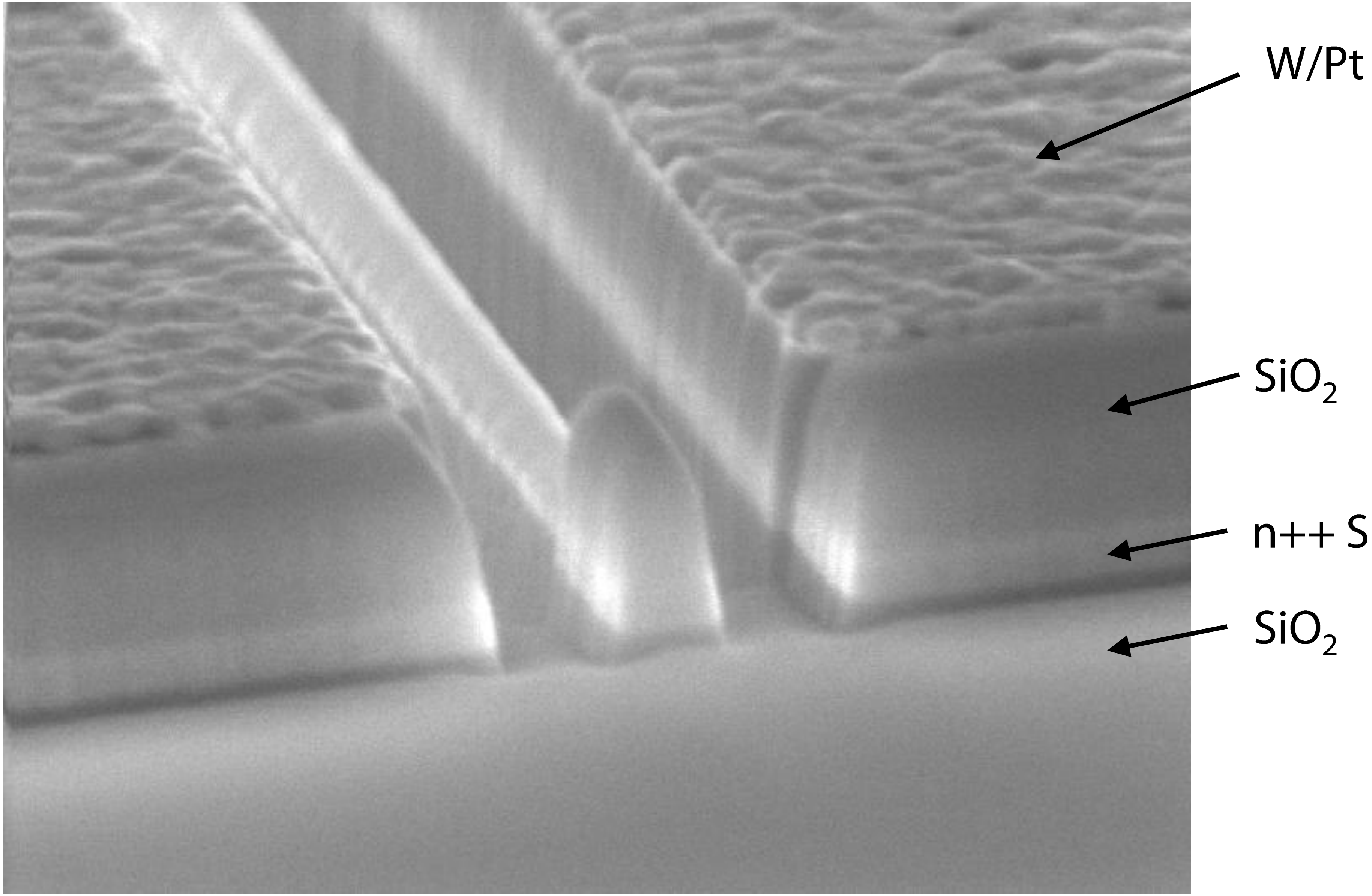

Cr
T_m = 2180 C
(sublimes at
1800 C)


Cr/Au
Au T_m = 1064 C

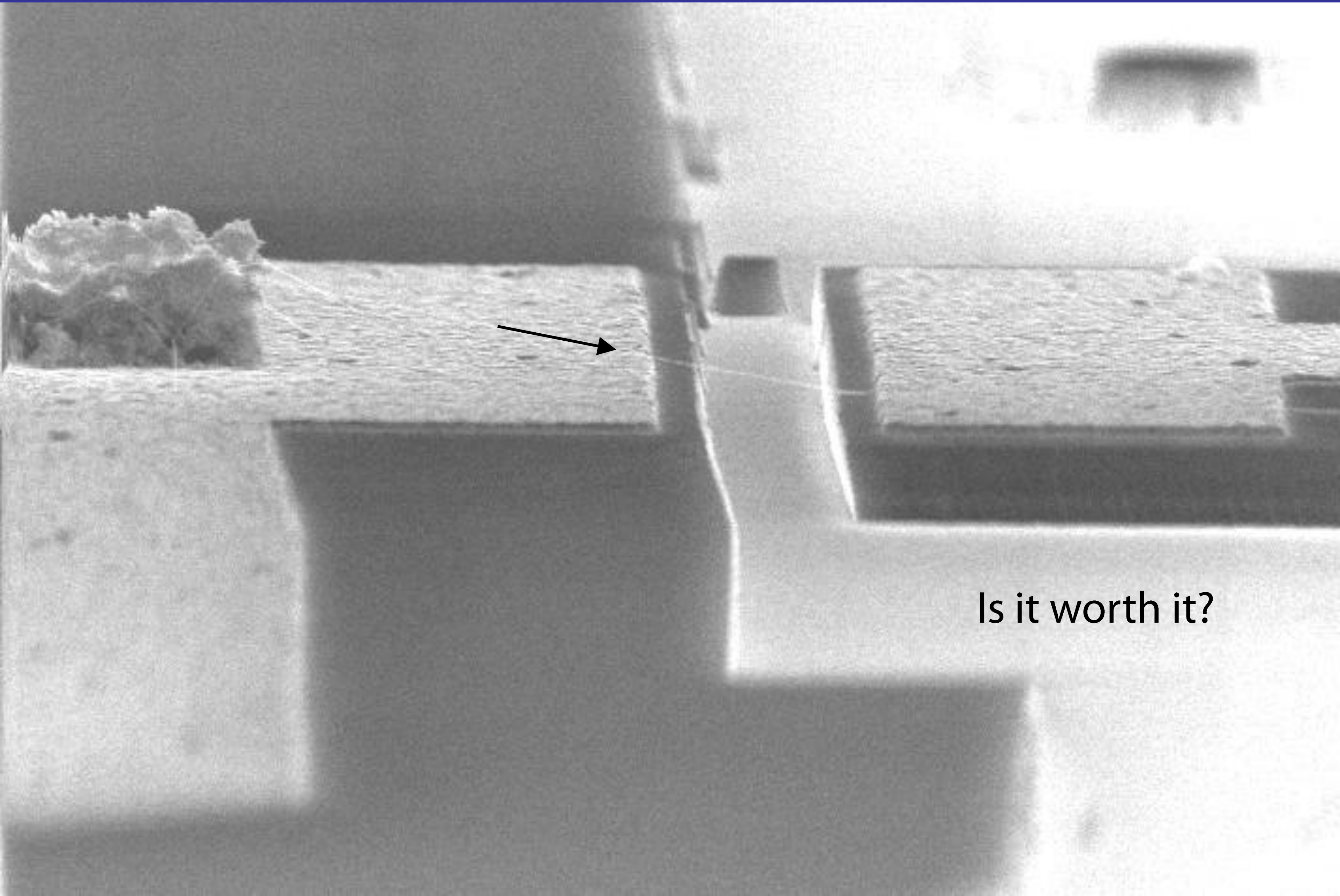

Pd
(nanotube catalyst)


Fe
(nanotube catalyst)

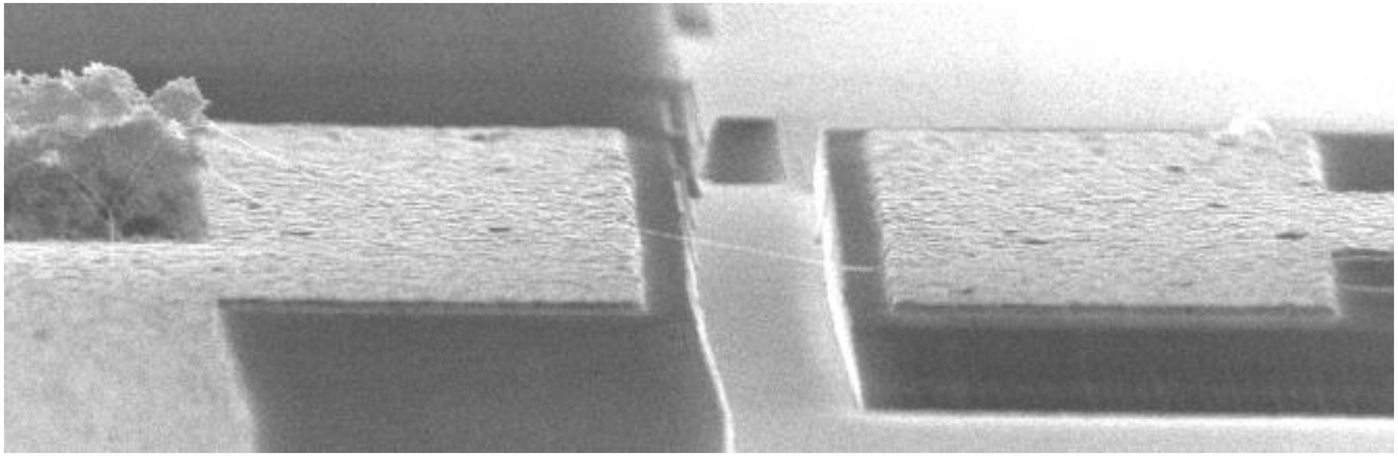
The Solution: W/Pt and Silicon!



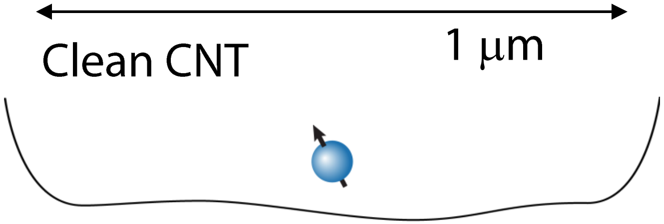
Then we need a nanotube…



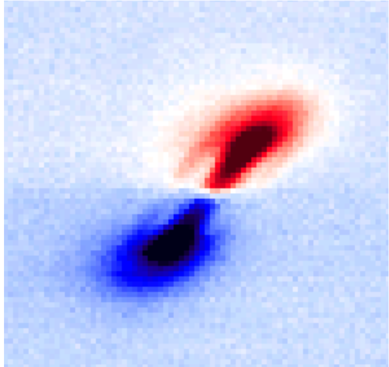
The advantages of clean



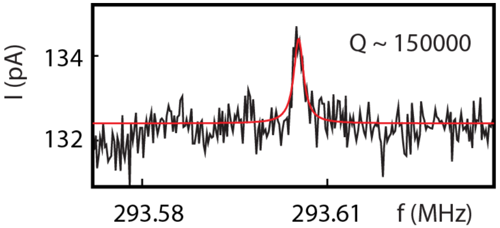
Extremely Low Disorder



Strong Interaction with Light



Exceptional mechancial properties

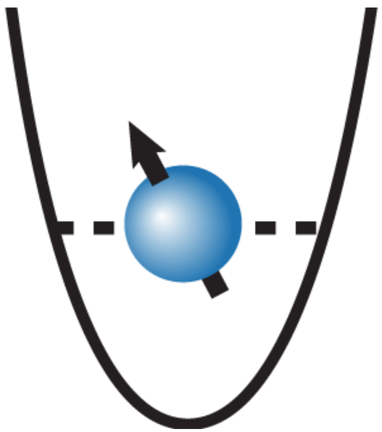


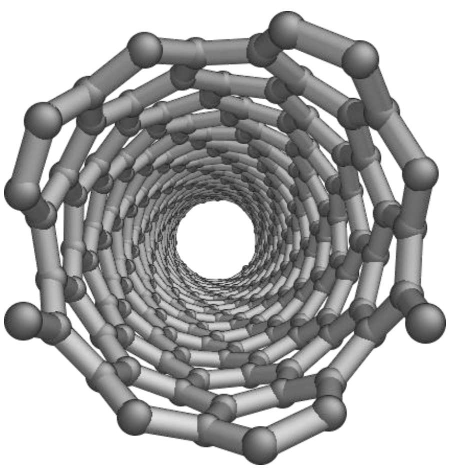
Clean nanotube quantum dots

Steele *et al*. Nature Nanotechnology (2009)

What is our motivation?

Spin Quantum Bit





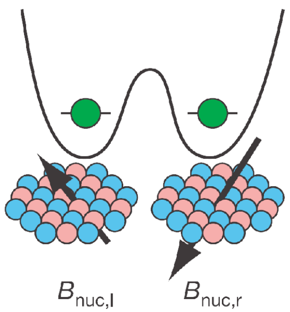
Use spin states of a single electron as a quantum bit

$|\uparrow\rangle$ $|\downarrow\rangle$

Why Spins? → Weakly coupled to the environment

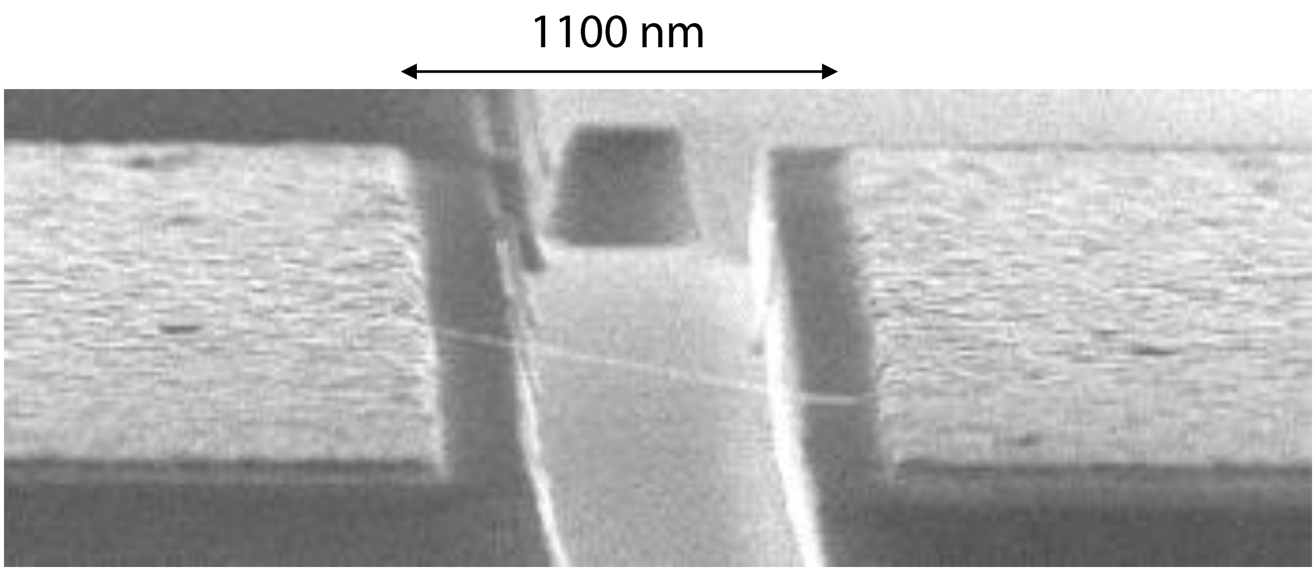
GaAs Spin Qubits:

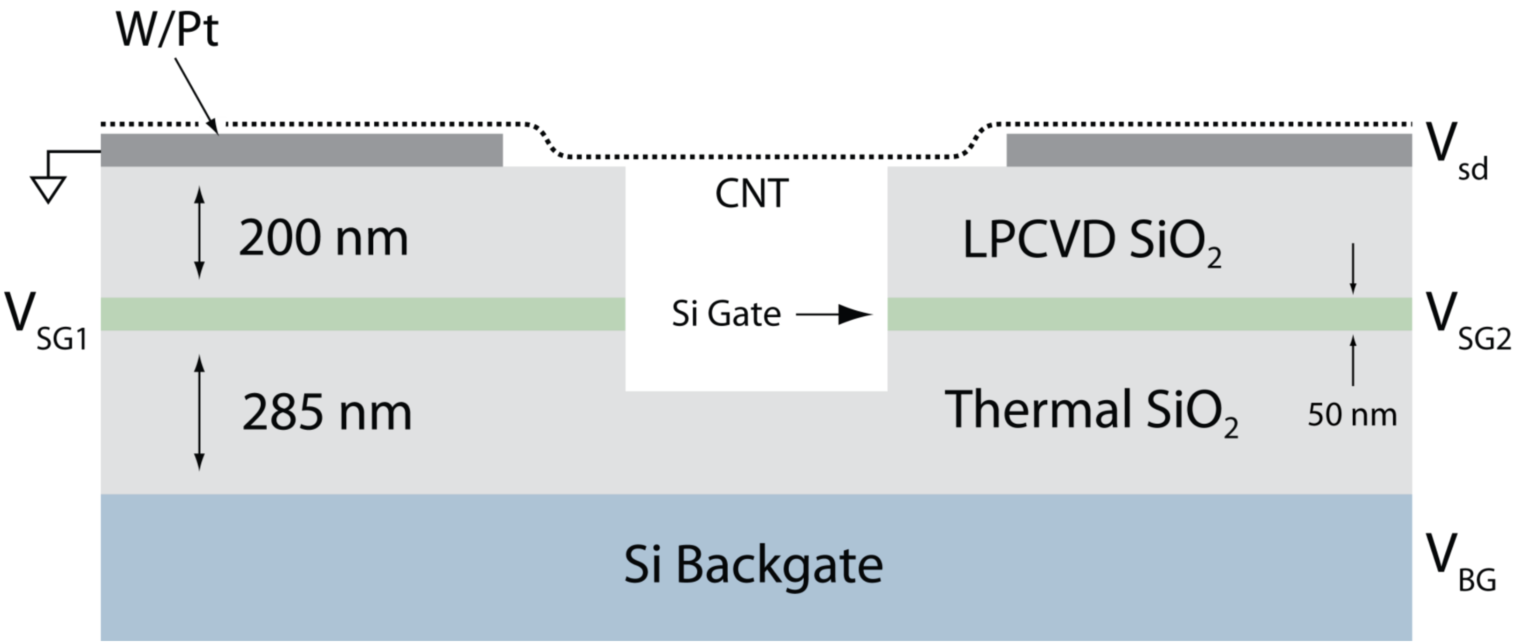
Problems with nuclear spins…



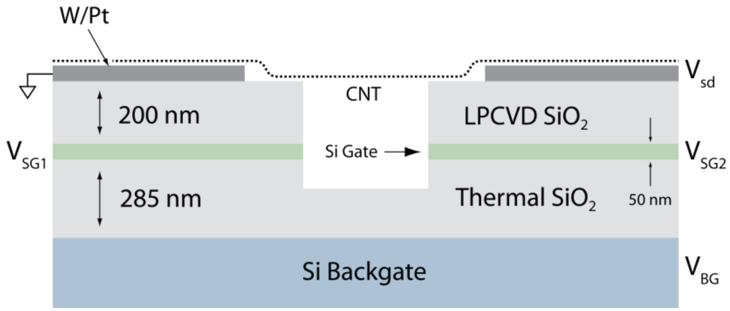
^{12}C Carbon Nanotubes: No Nuclear spins

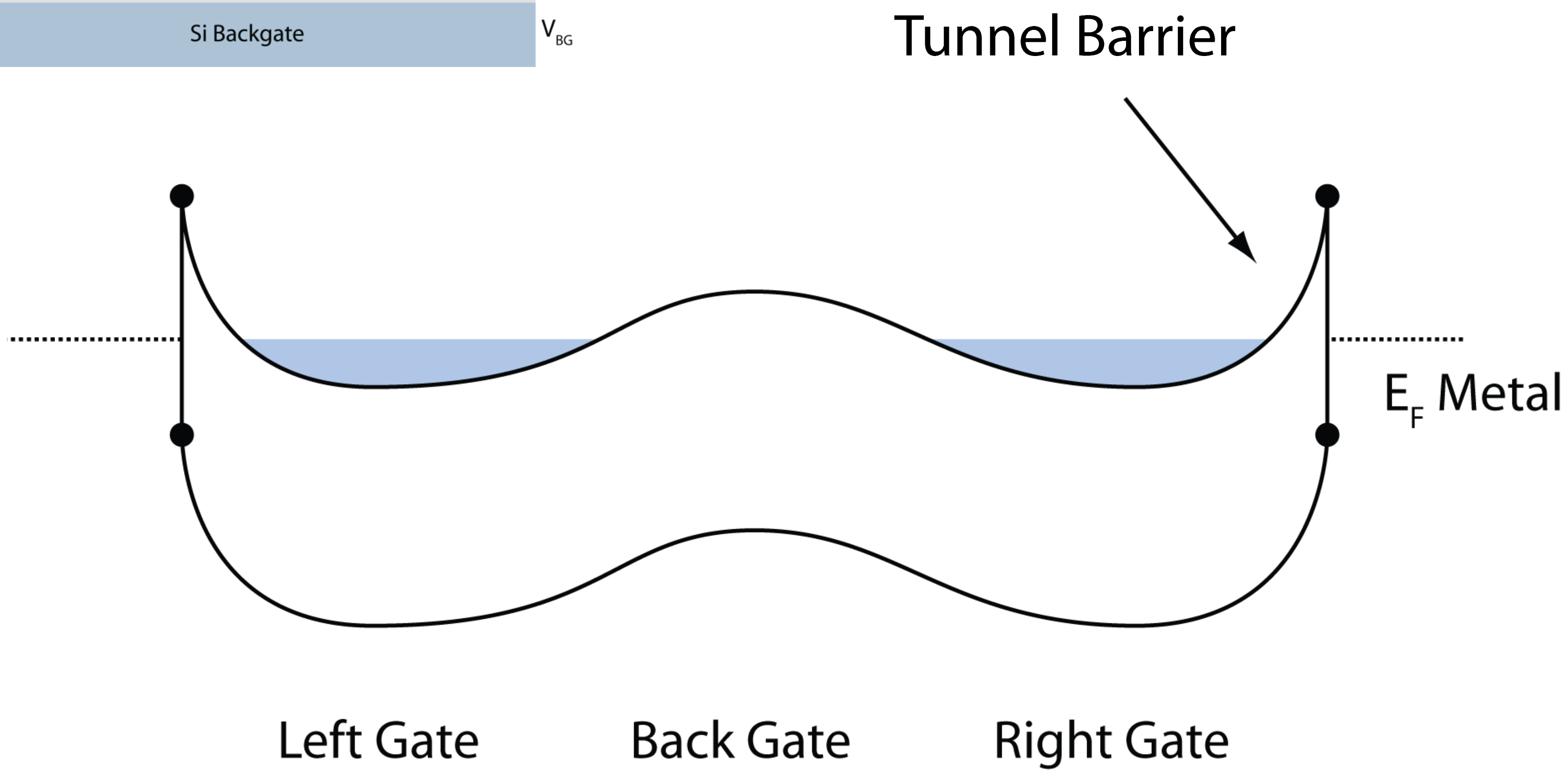
Nanotube quantum dots: The Device



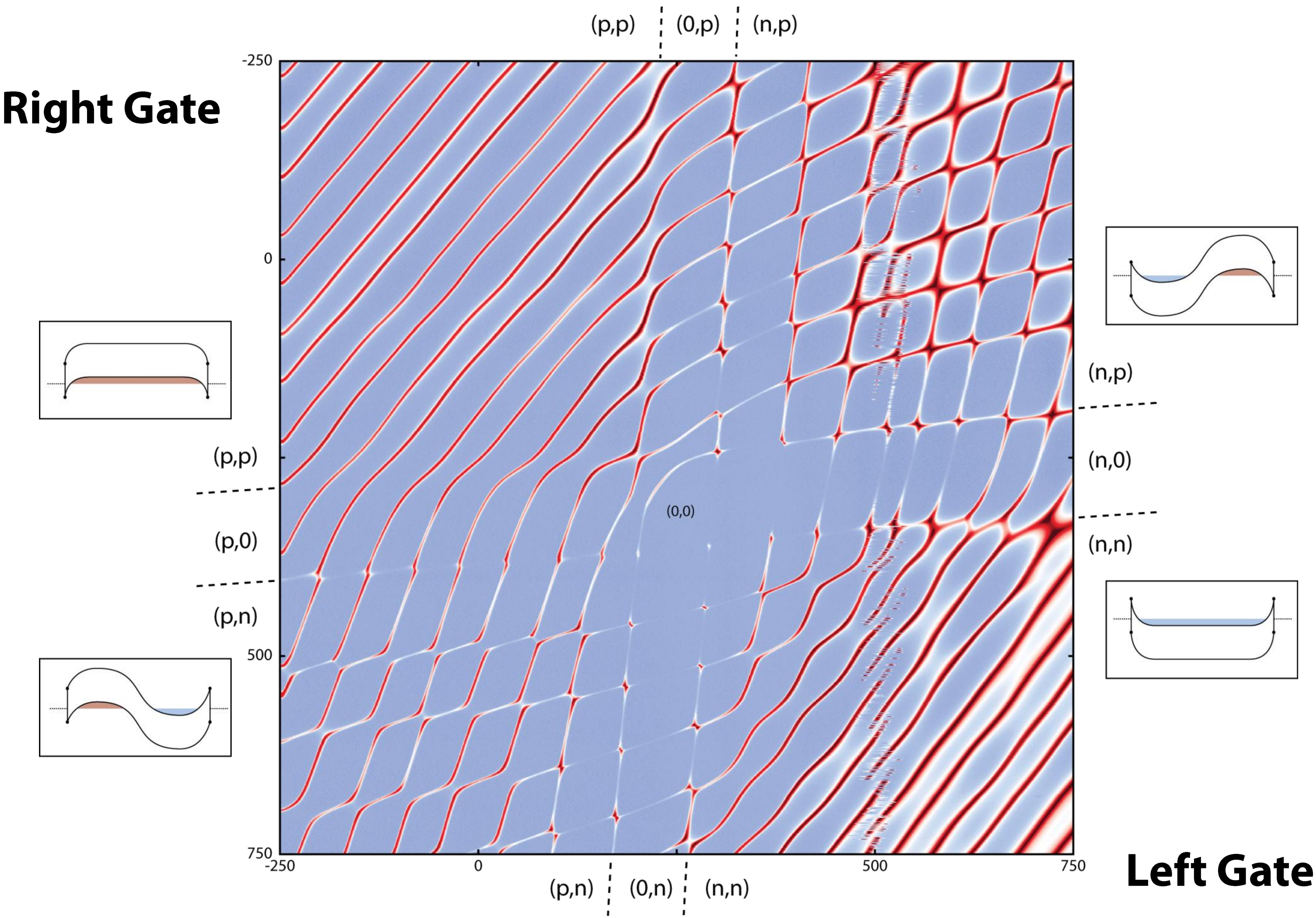


A quantum dot with three gates

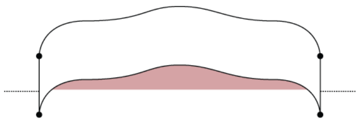


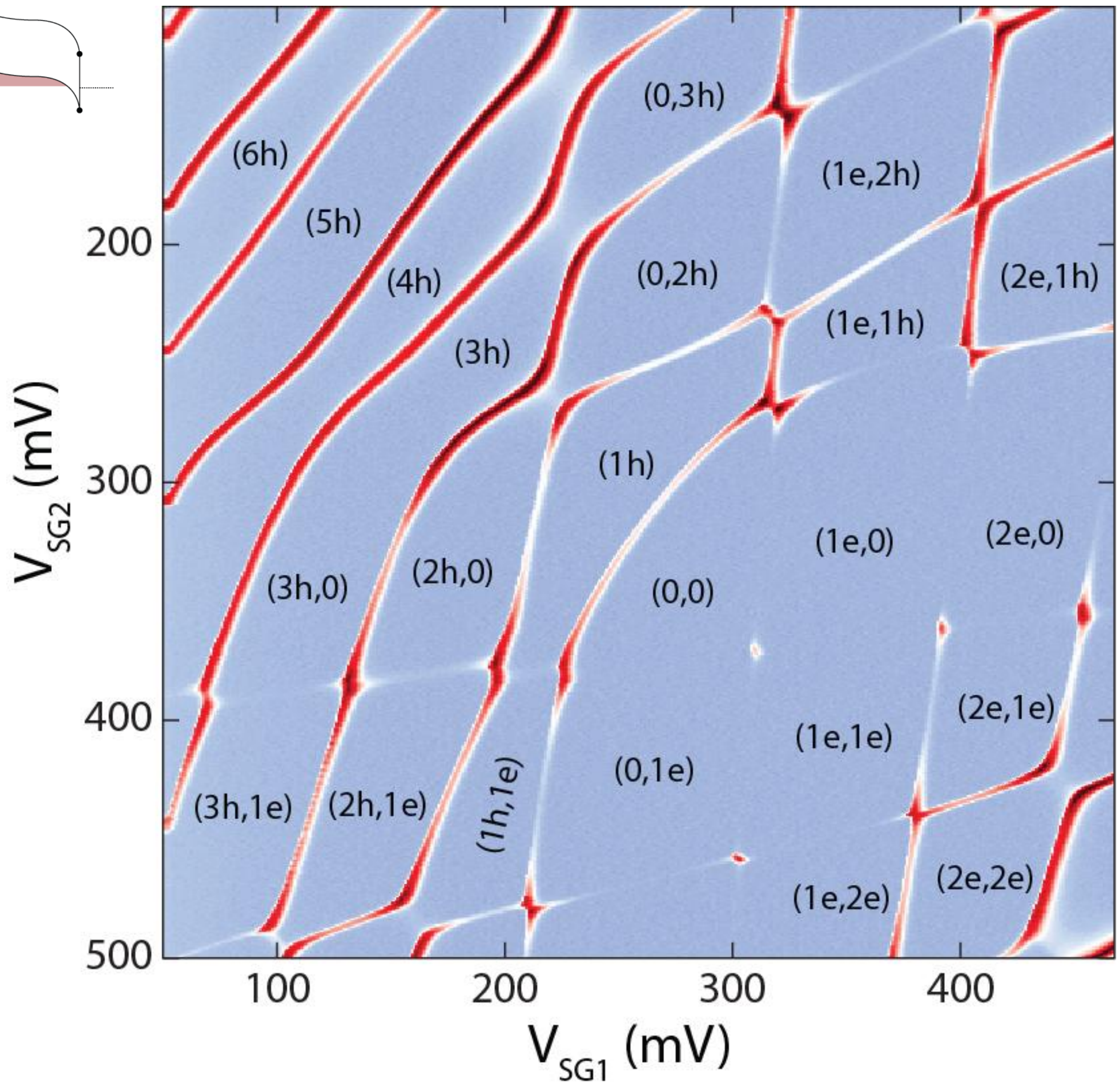


Finding the last electron

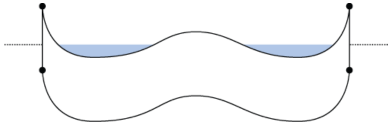


A double quantum dot

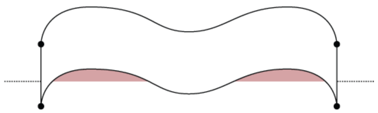


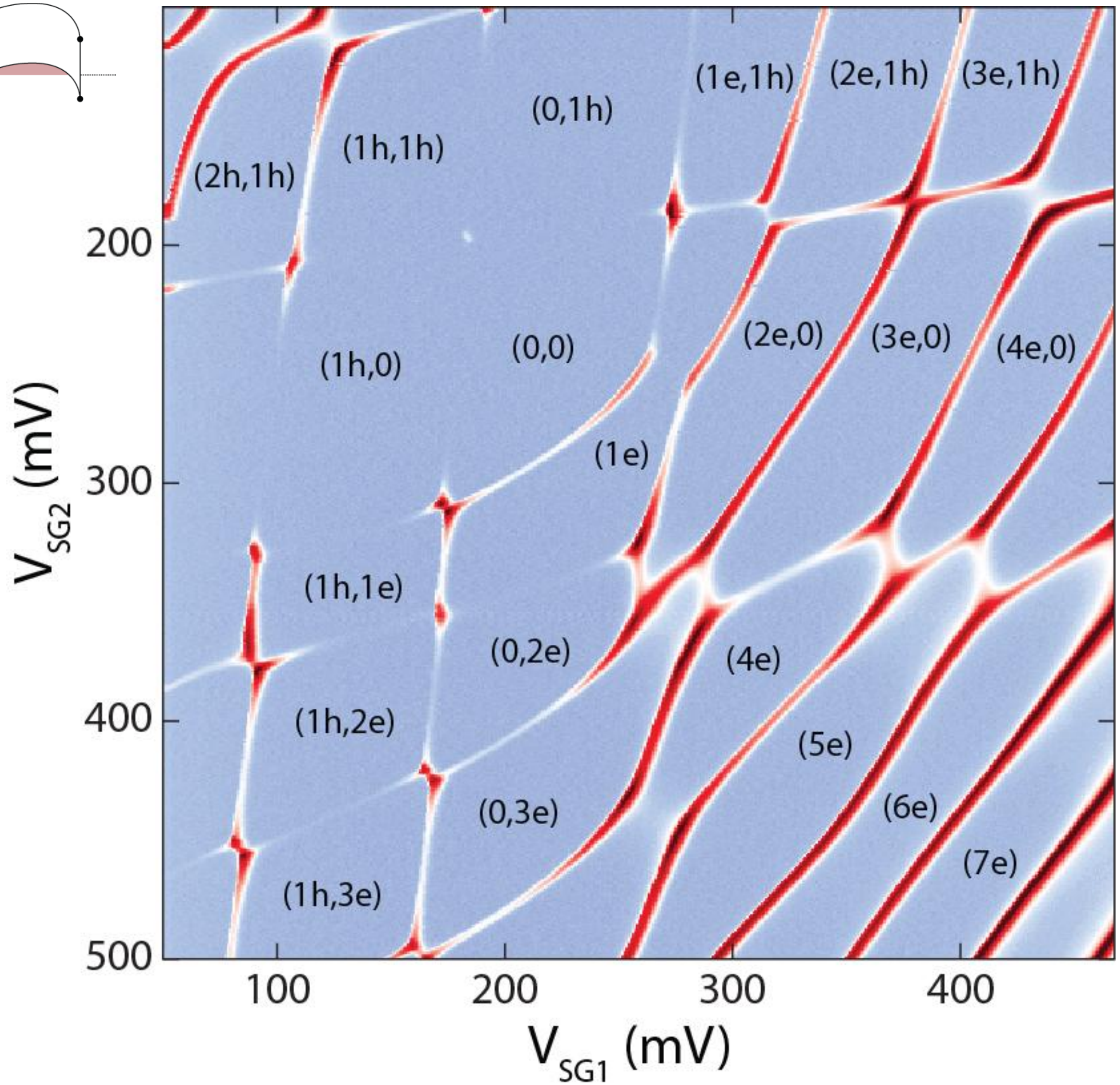


$V_{BG} = 0$ mV

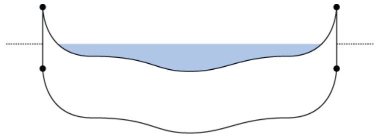


That we can control

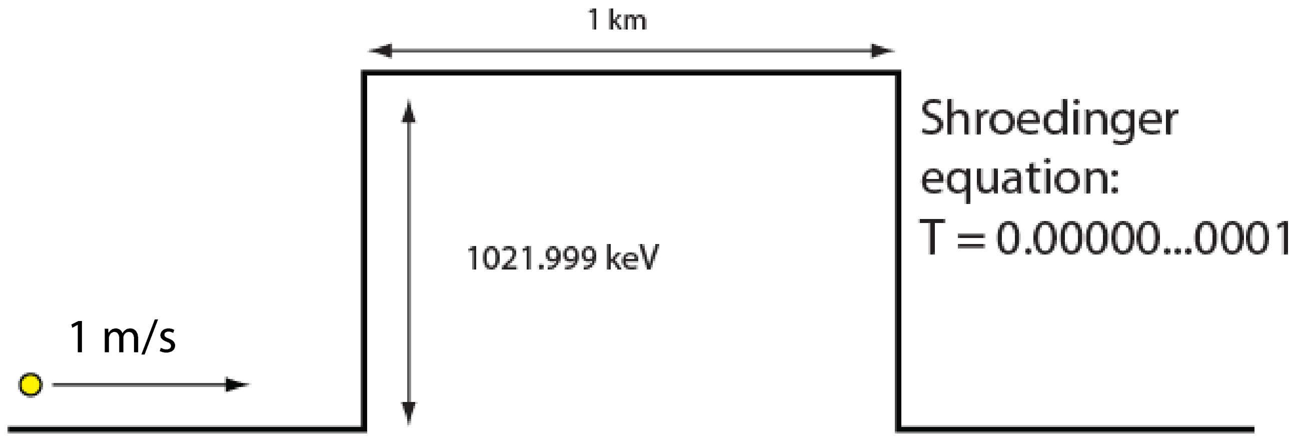


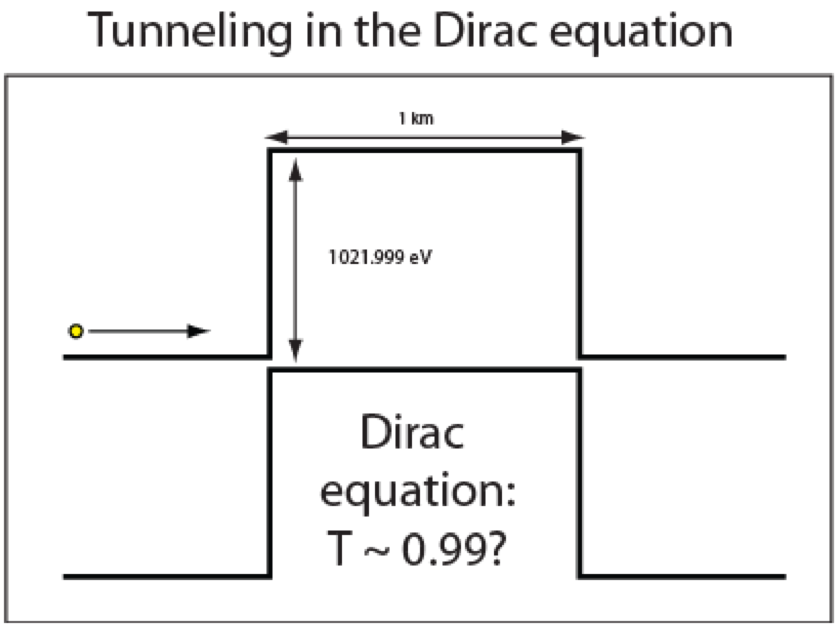


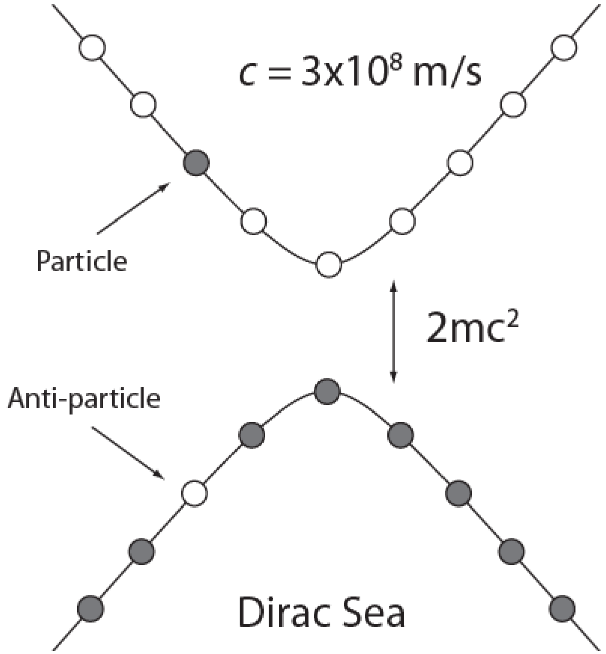
$V_{BG} = 250$ mV



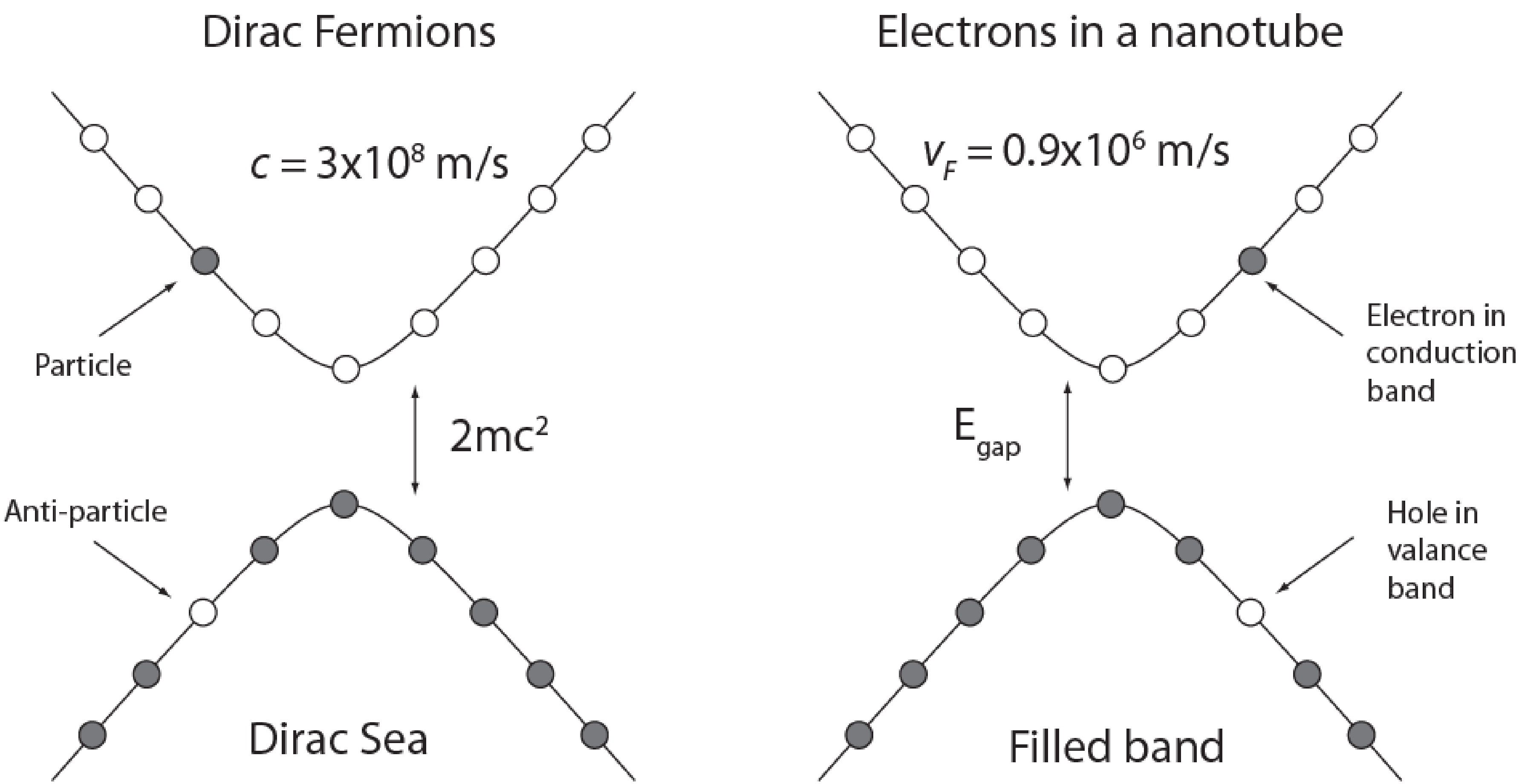
Klein Tunneling: What is Klein Tunneling?



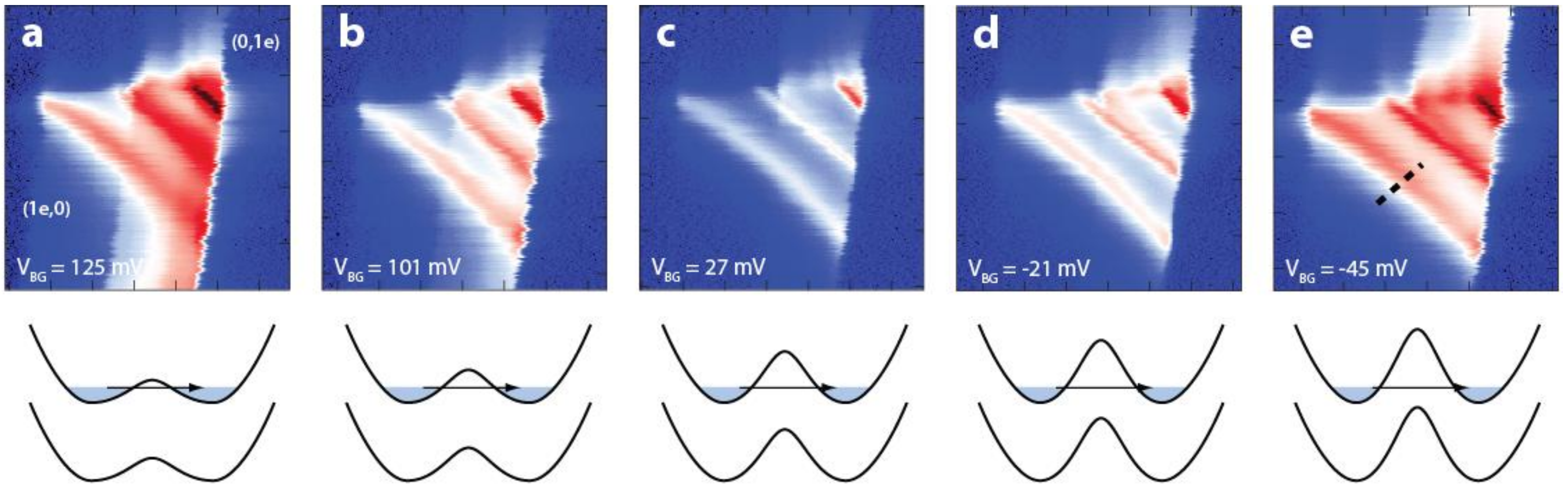




What does this have to do with nanotubes?



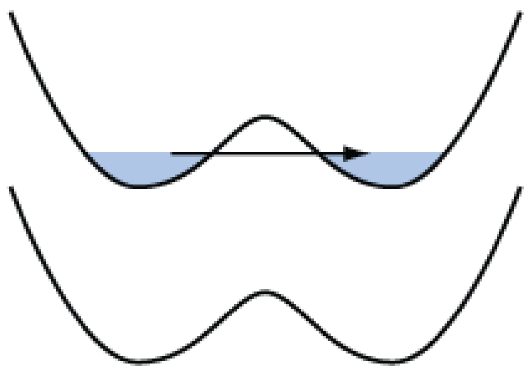
Klein Tunneling in a nanotube

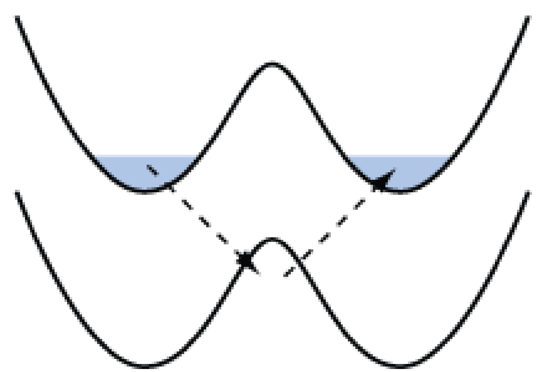


Current decreases as barrier goes up

Current *increses* as barrier goes up?

Normal Tunneling





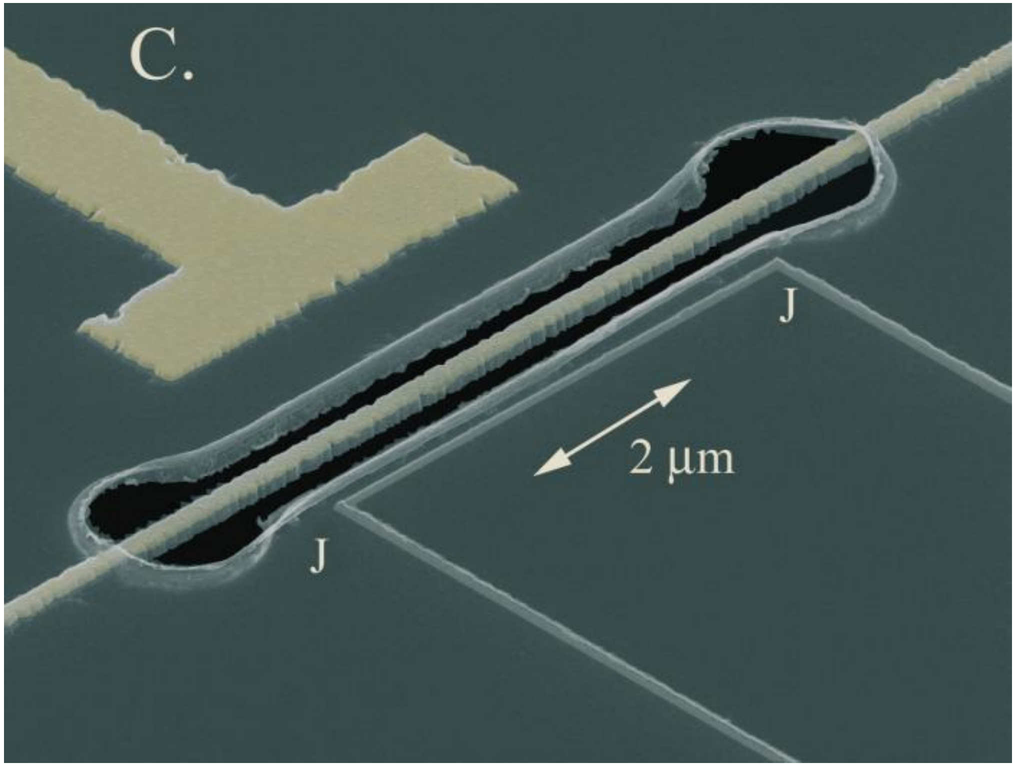
Klein Tunneling

Nanotube Nanomechanics

Huettel *et al*. NanoLetters (2009)

Steele *et al*. Science (2009)

Nanomechanical Resonators



A SiN beam resonator

Why nano?

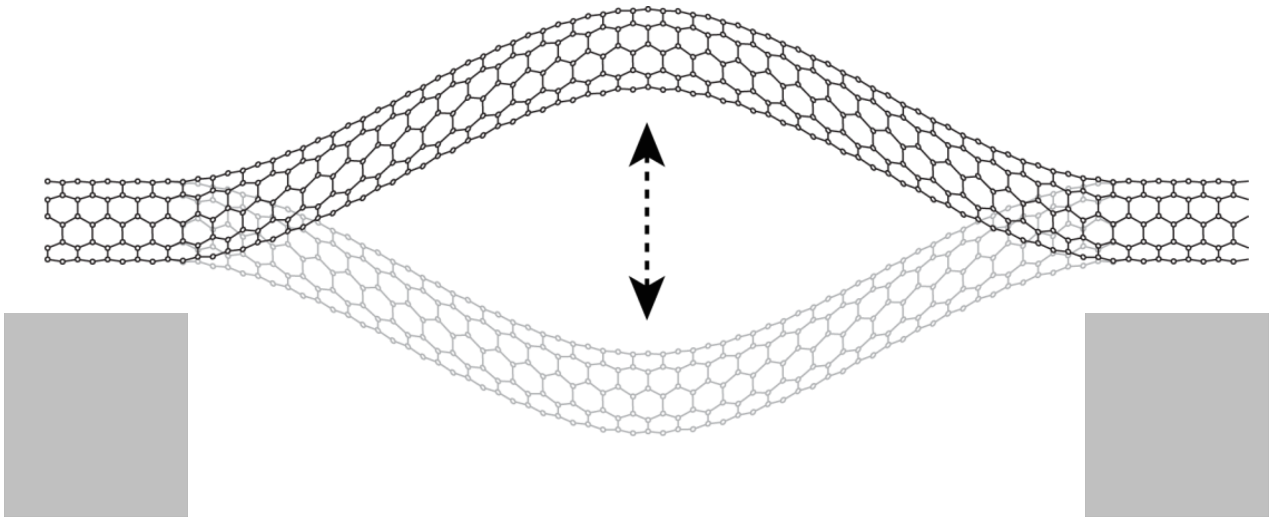
$$\omega = \sqrt{\frac{k}{m}} \qquad \text{If} \quad \hbar\omega > k_B T$$

"quantum limit of macroscopic motion"

$$\omega = \sqrt{\frac{k}{m + dm}}$$

Mass sensing: if *m* is small, then we can detect small changes *dm* of the resonator

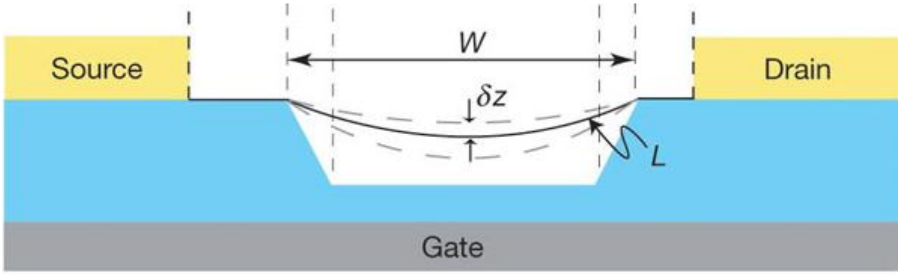
Why nanotubes?

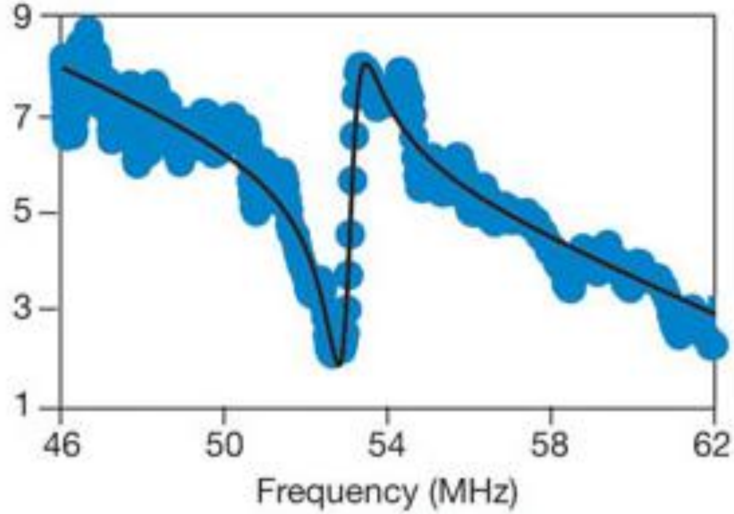


Nanotubes:

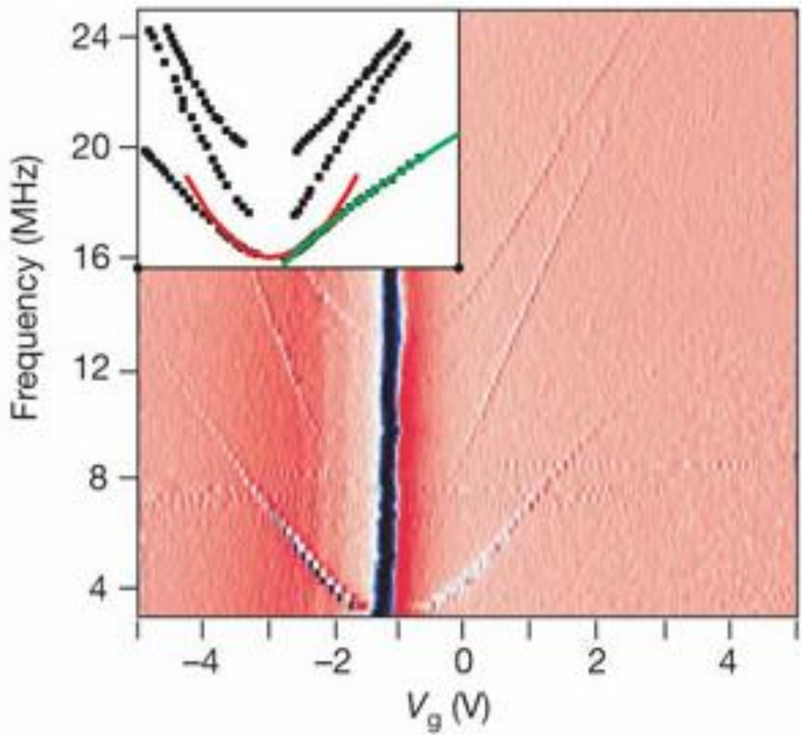
Light	Stiff	High Q?
10^{-21} kg vs. 10^{-18} kg	Large Young's Modulus	Single crystal, No etching defects

Tunable Nanotube Resonators





Sazanova *et al.*, Nature **431**, 284 (2004)

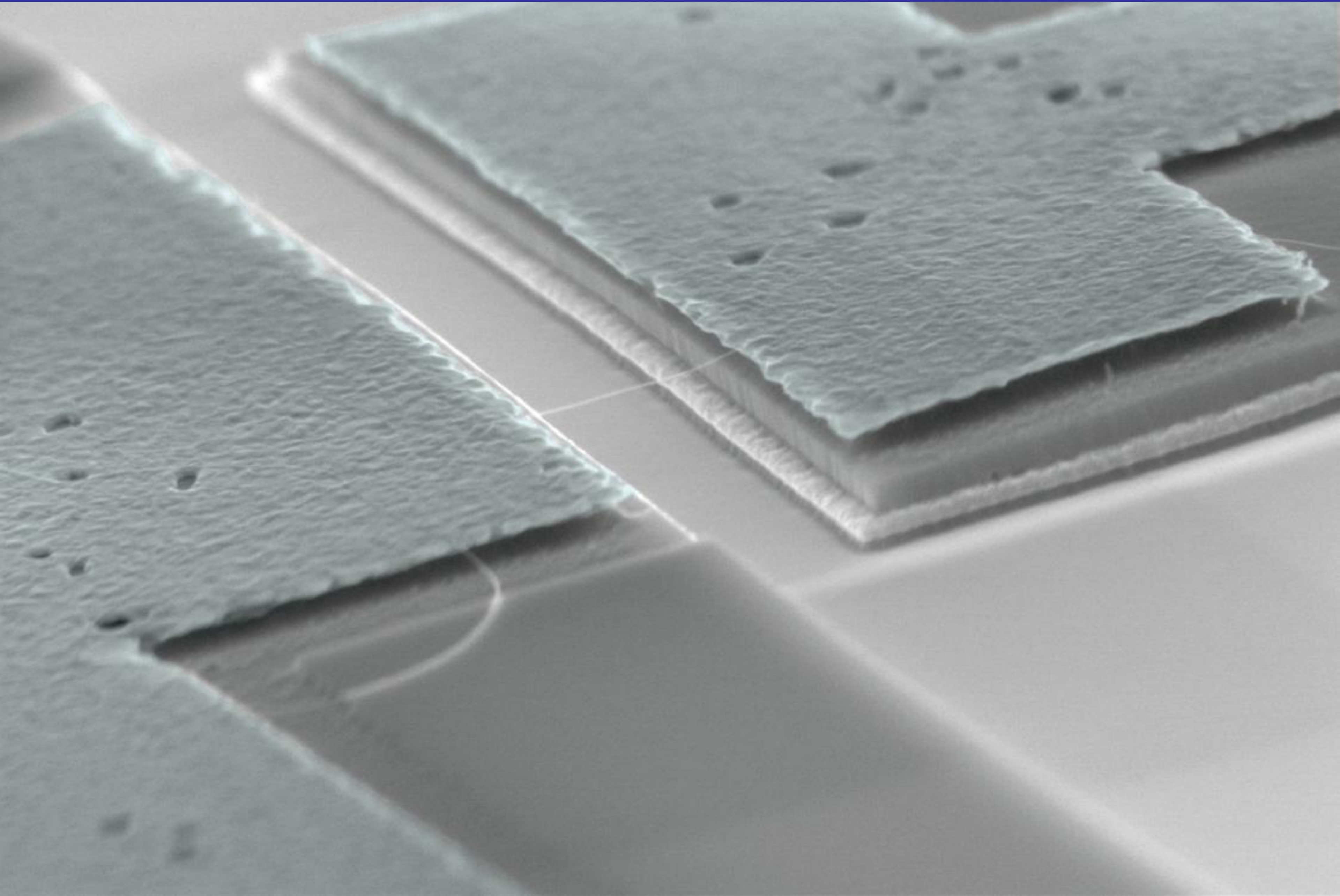


Q = 80? (2004)

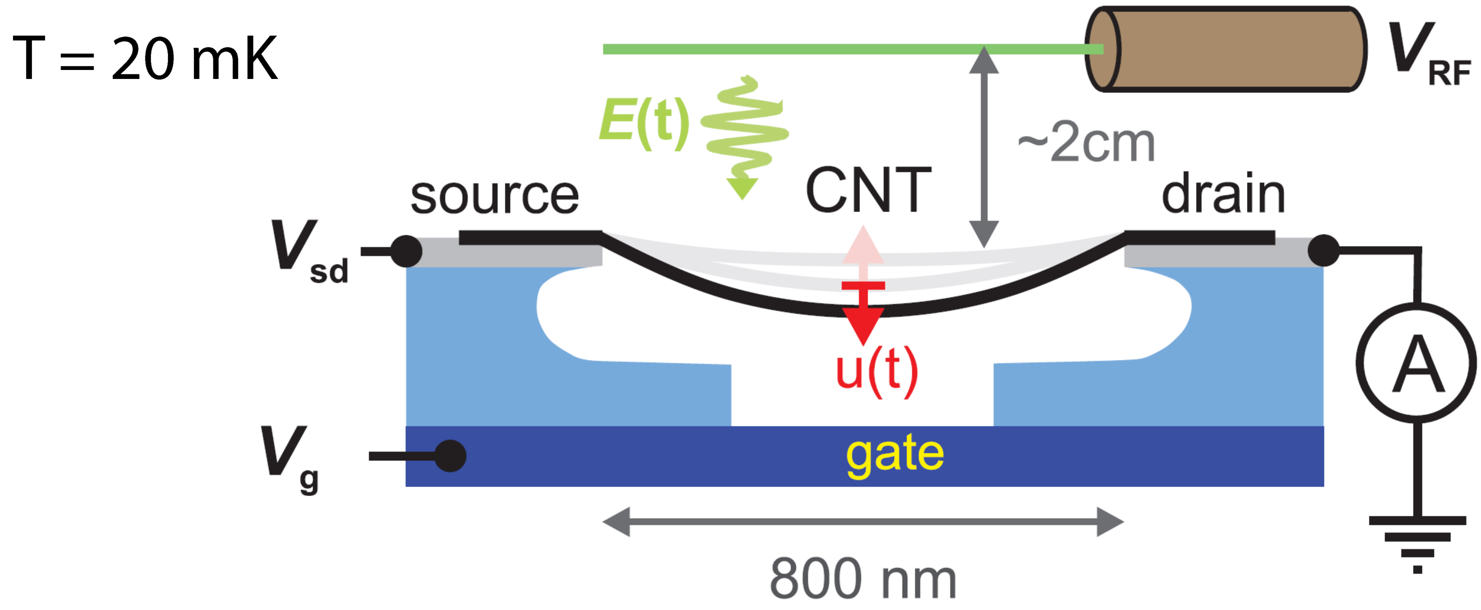
(Recent results: Q ~ 1000 at 1.2K in 2008)

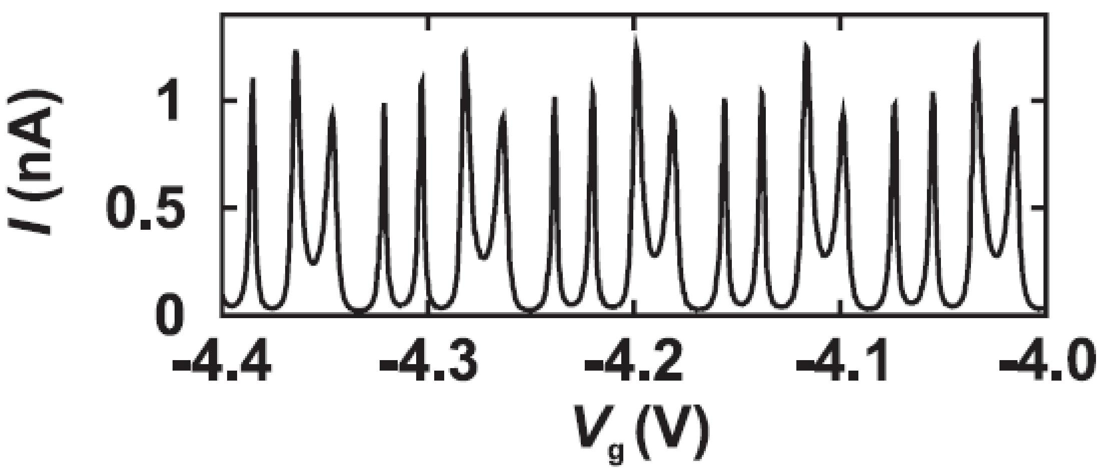
Where is the high Q?

Suspended nanotube quantum dot



Our measurement



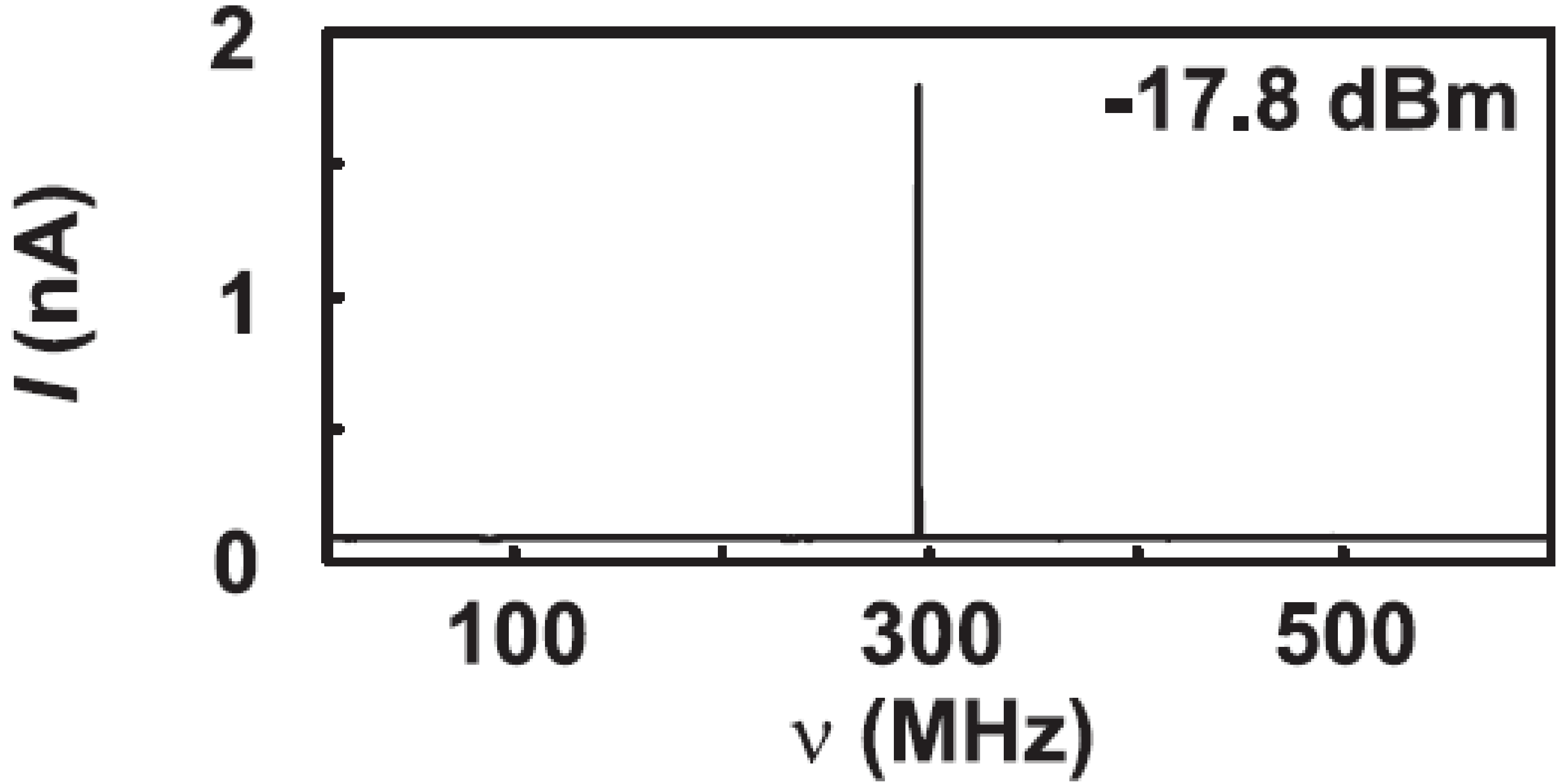


Apply RF

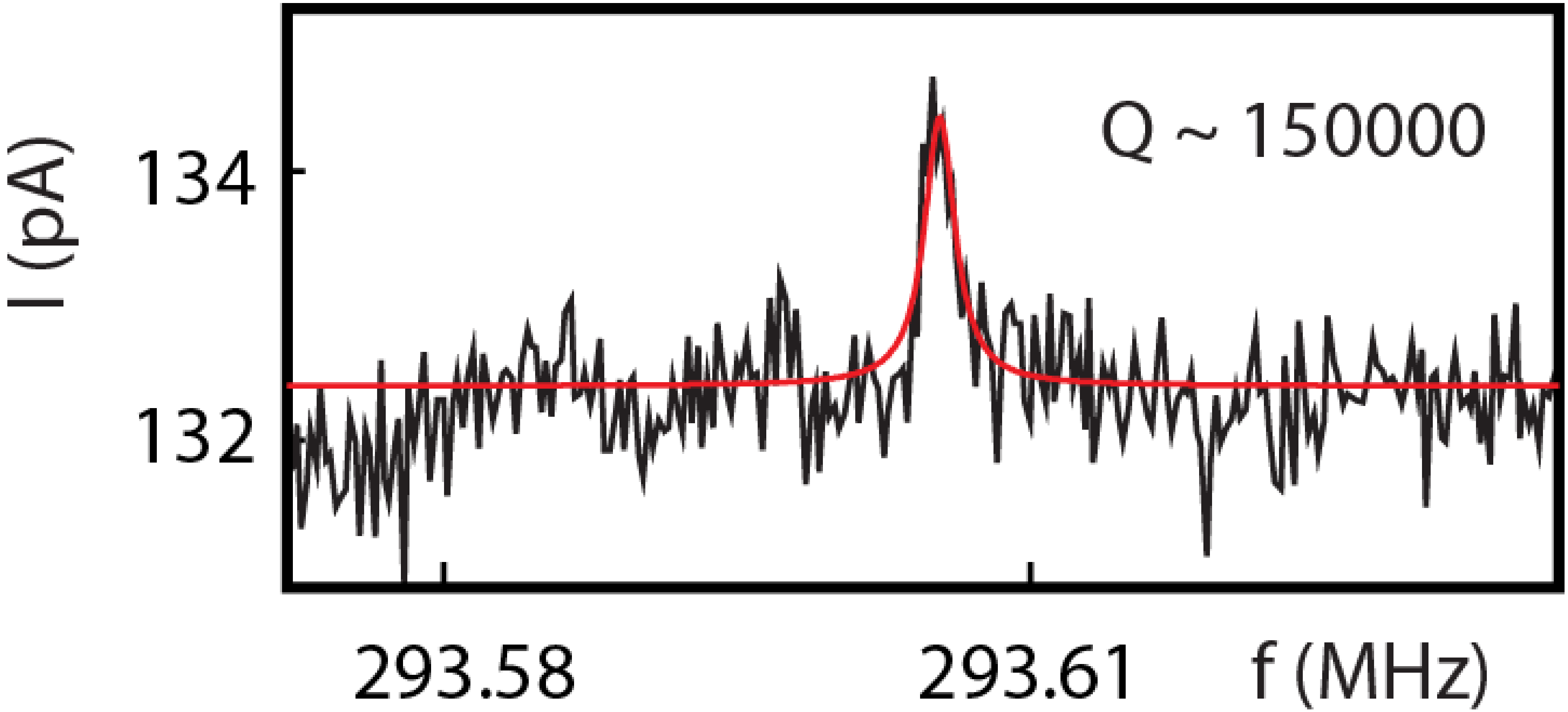
Measure DC Current

Sweep Frequency

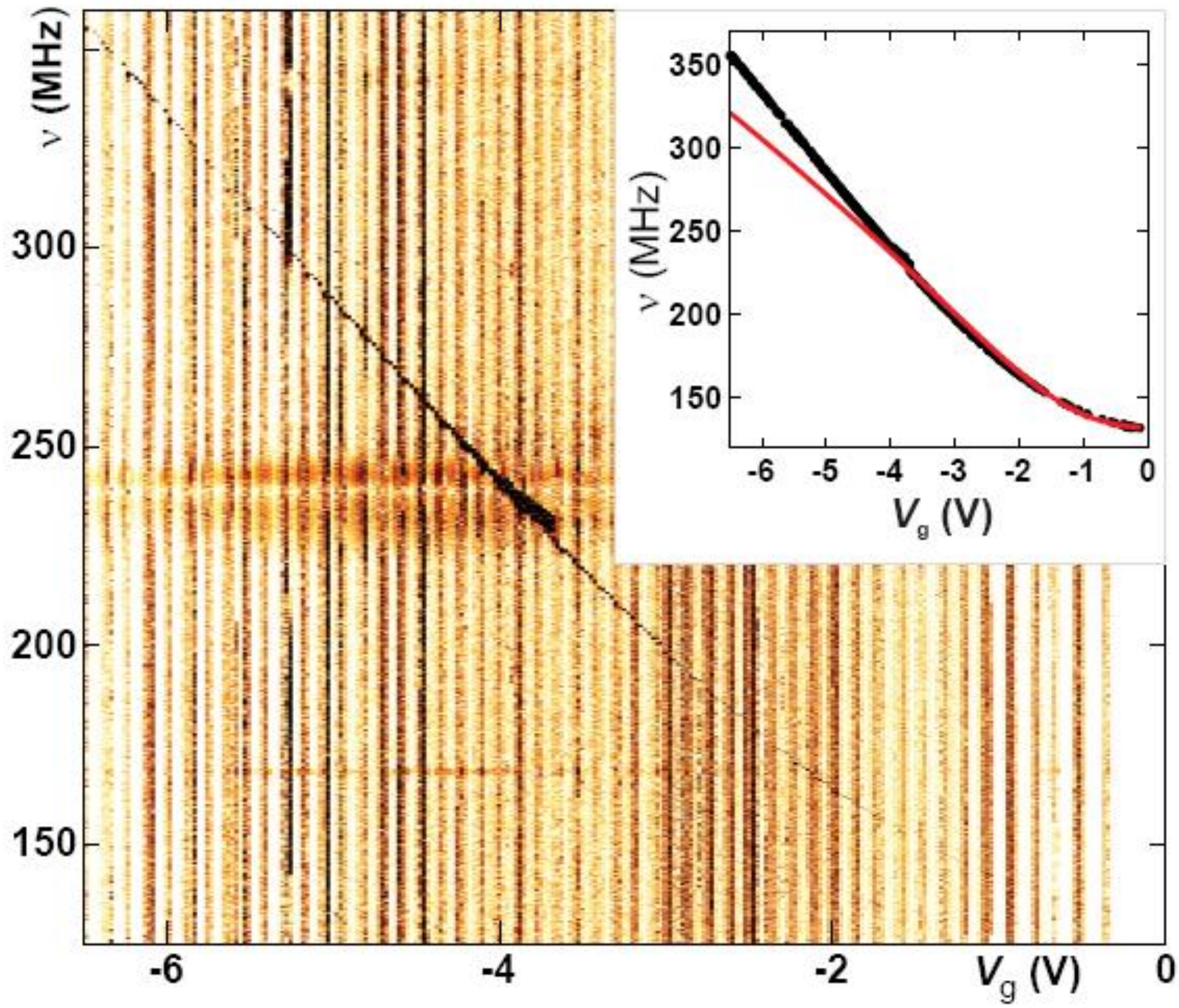
A resonance



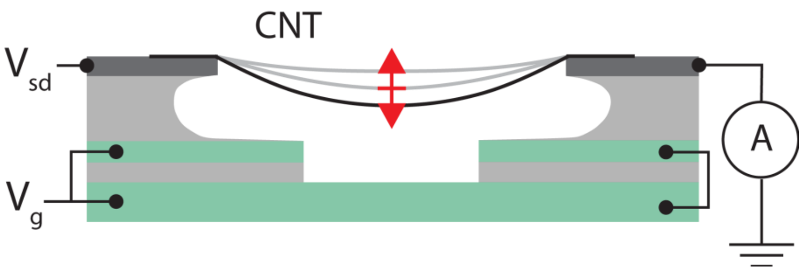
Very high Q-factor!

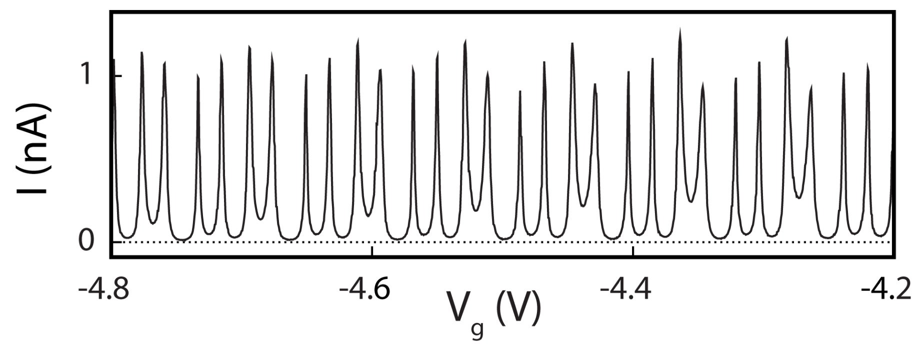


Mechanical Signature of the Resonance

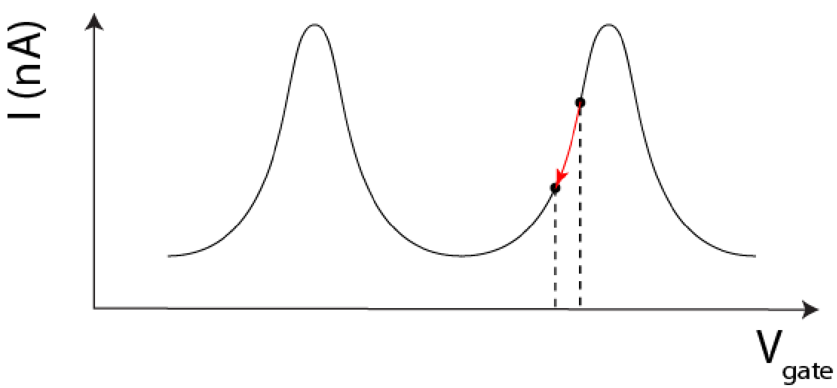


How do we detect mechanical motion?

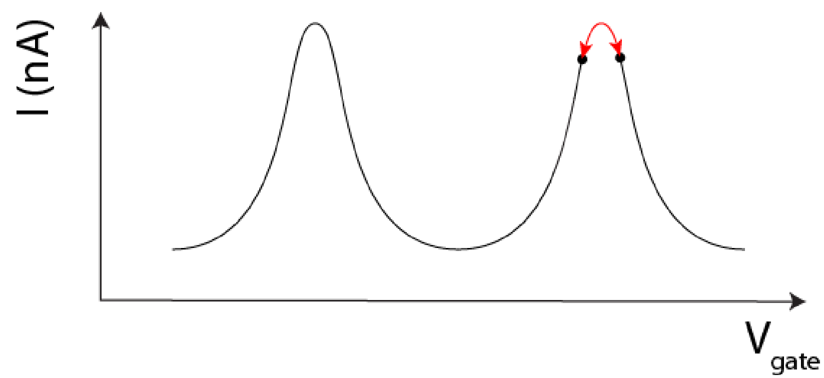




$Q_{dot} = C_g V_g$ $\quad$ $C_g = C_g(z)$

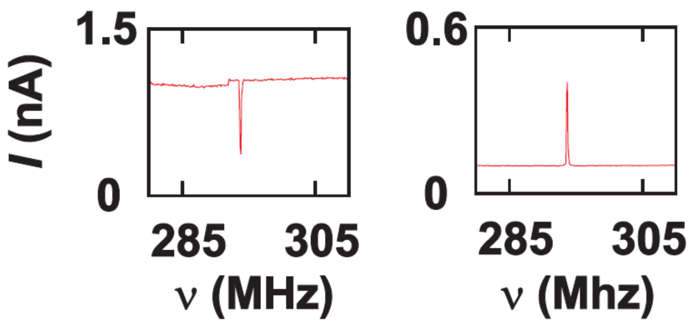


Move nanotube
= Effective Change in Gate Voltage



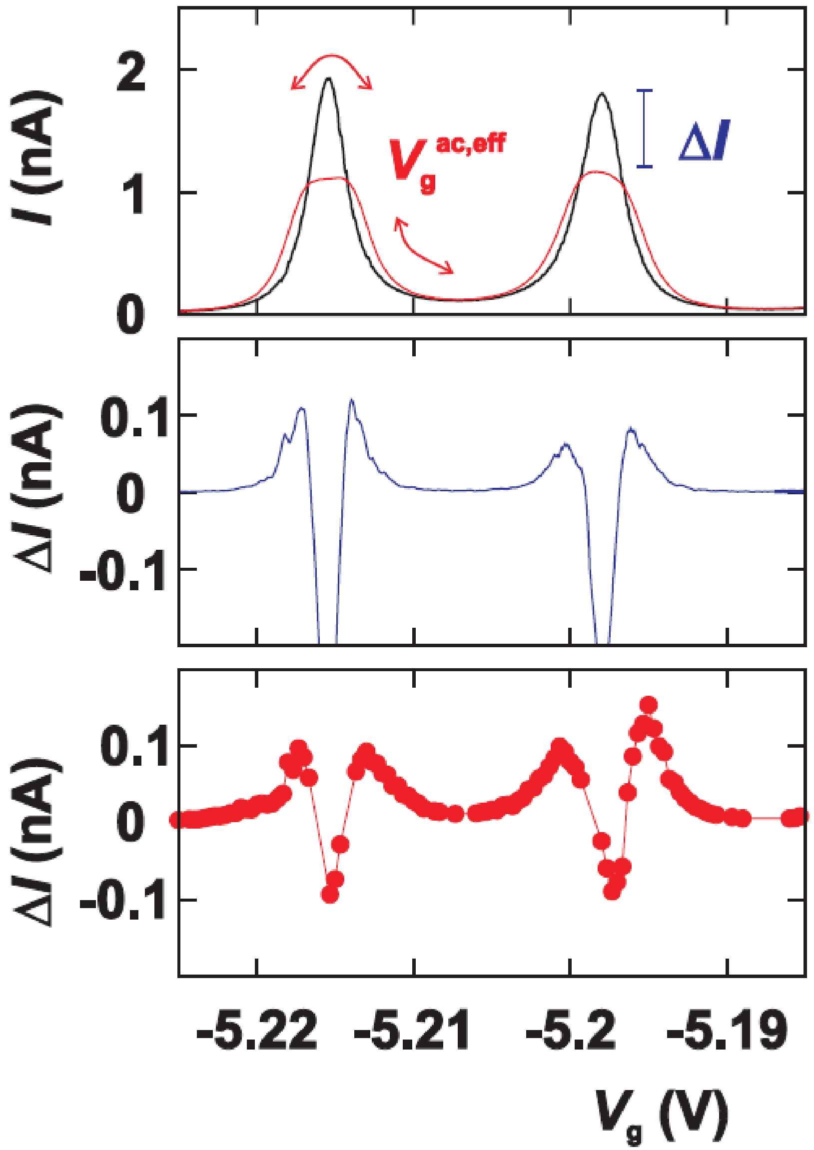
Oscillating nanotube:
Change DC Current

Detection Mechanism: Rectification

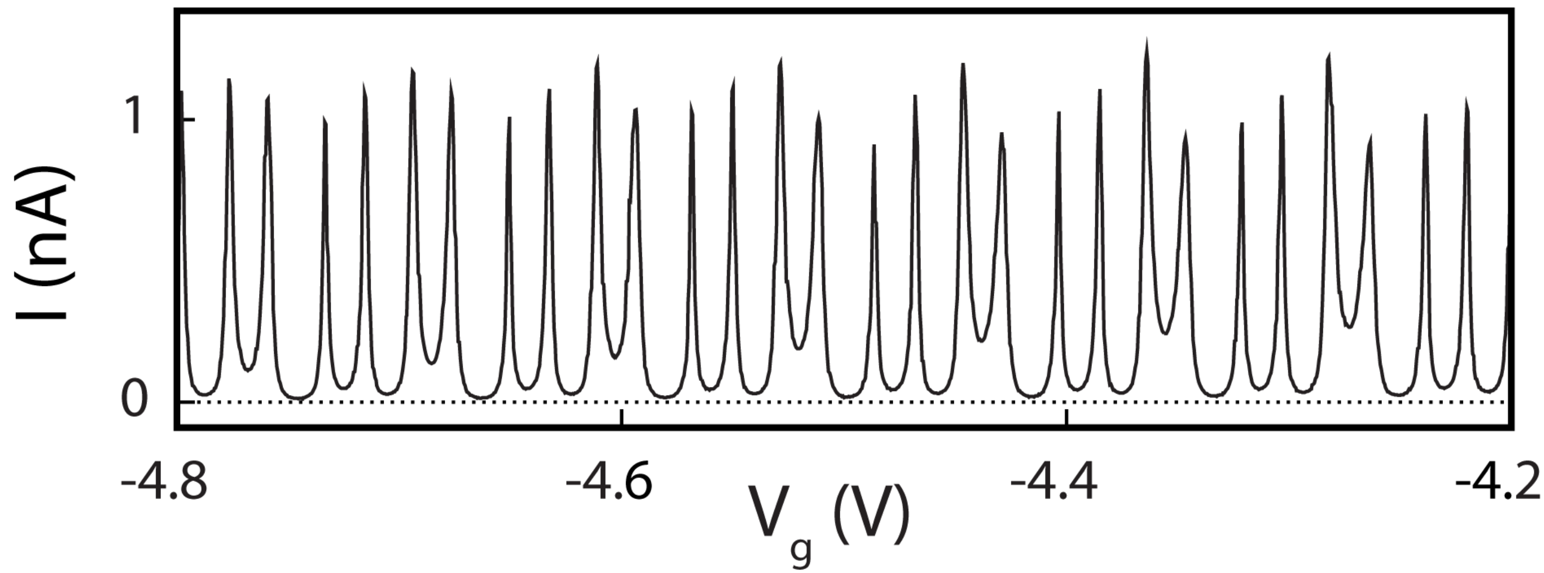


Resonance Signal can have either positive or negative sign

$$\Delta I \propto \frac{\partial^2 I}{\partial V_G^2}$$



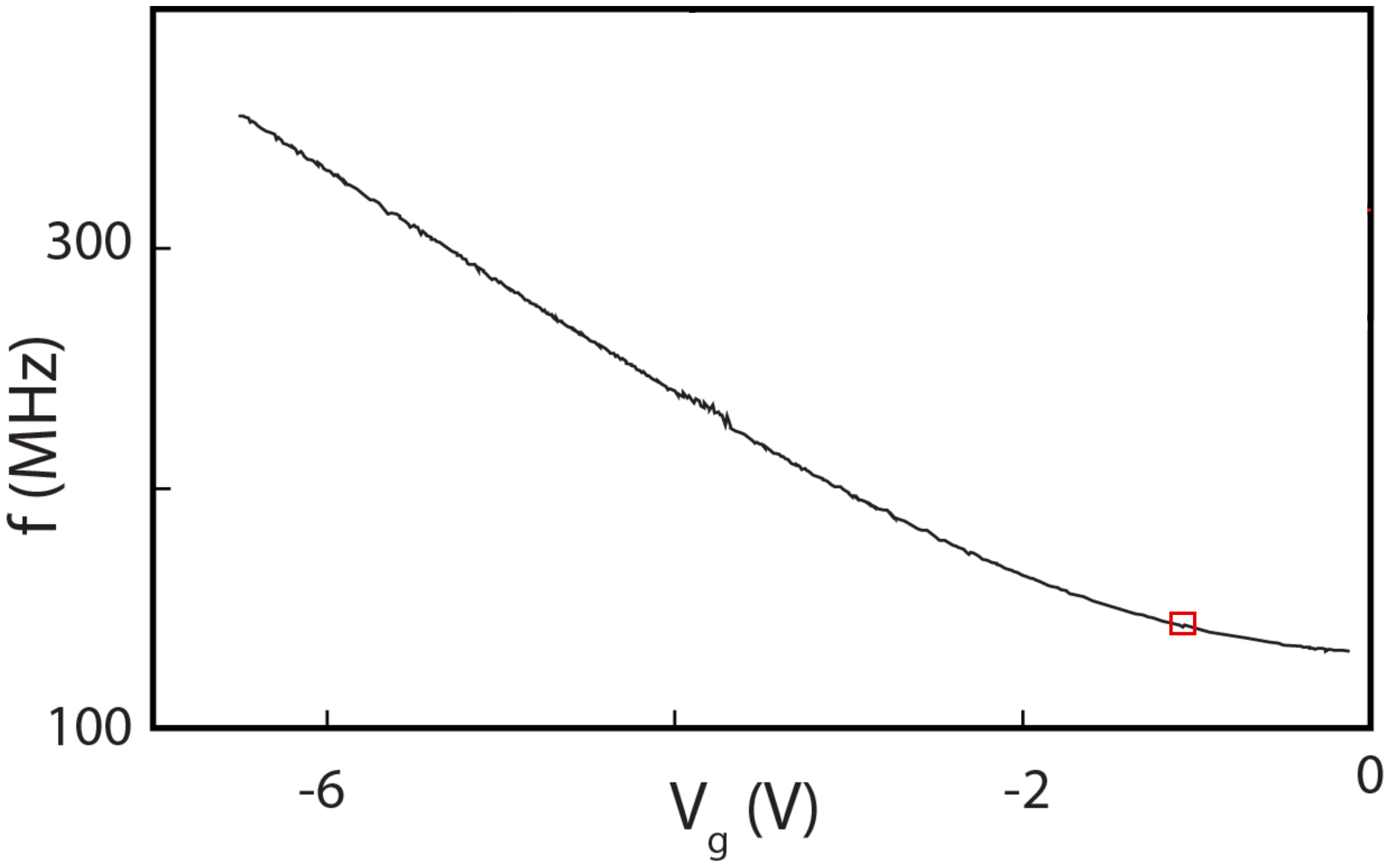
Quantum dot detector



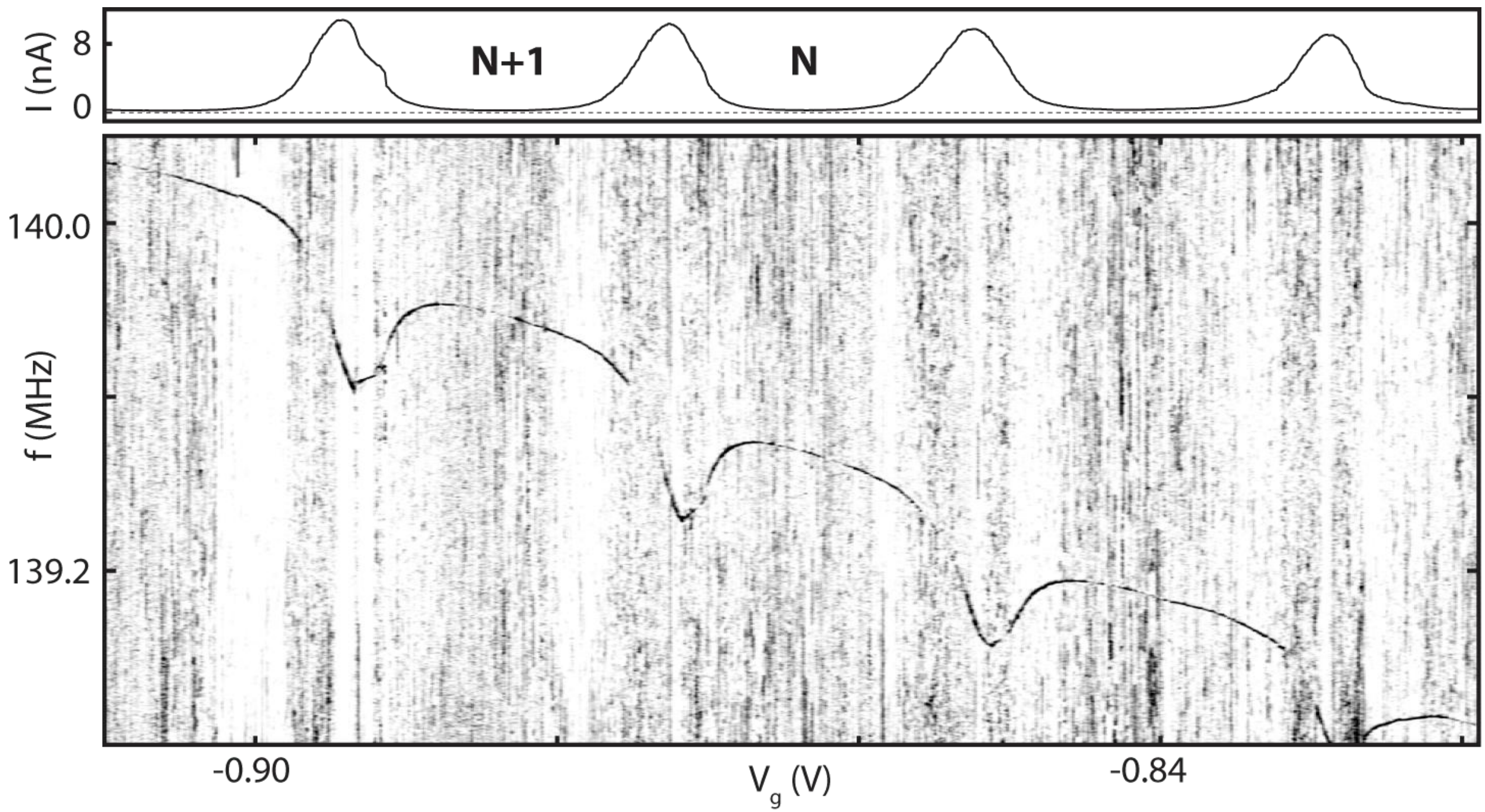
Quantum dot: detects mechanical motion

Can it also influence it?

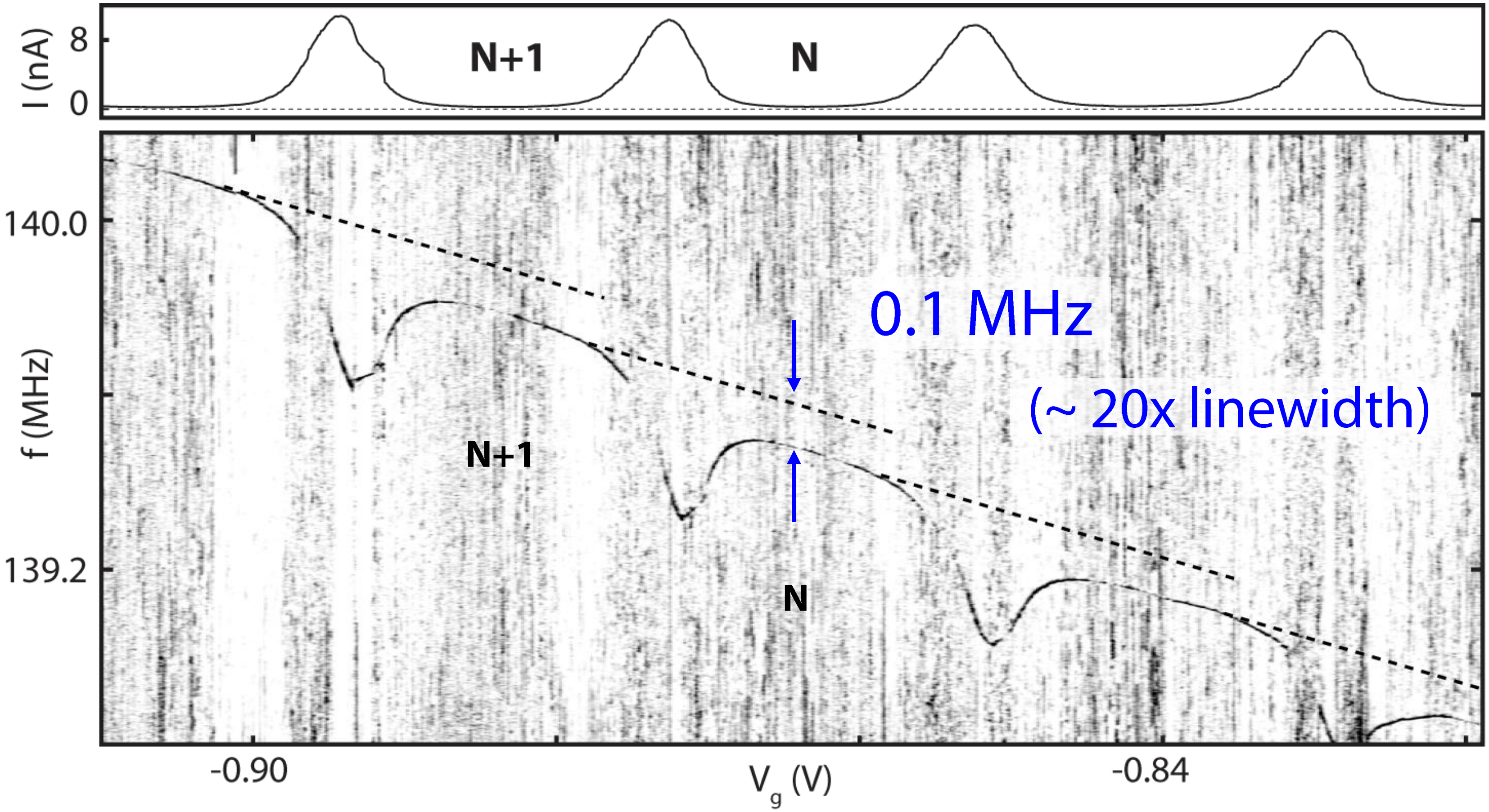
Zoom in



Tuning a Resonator with a Quantum Dot

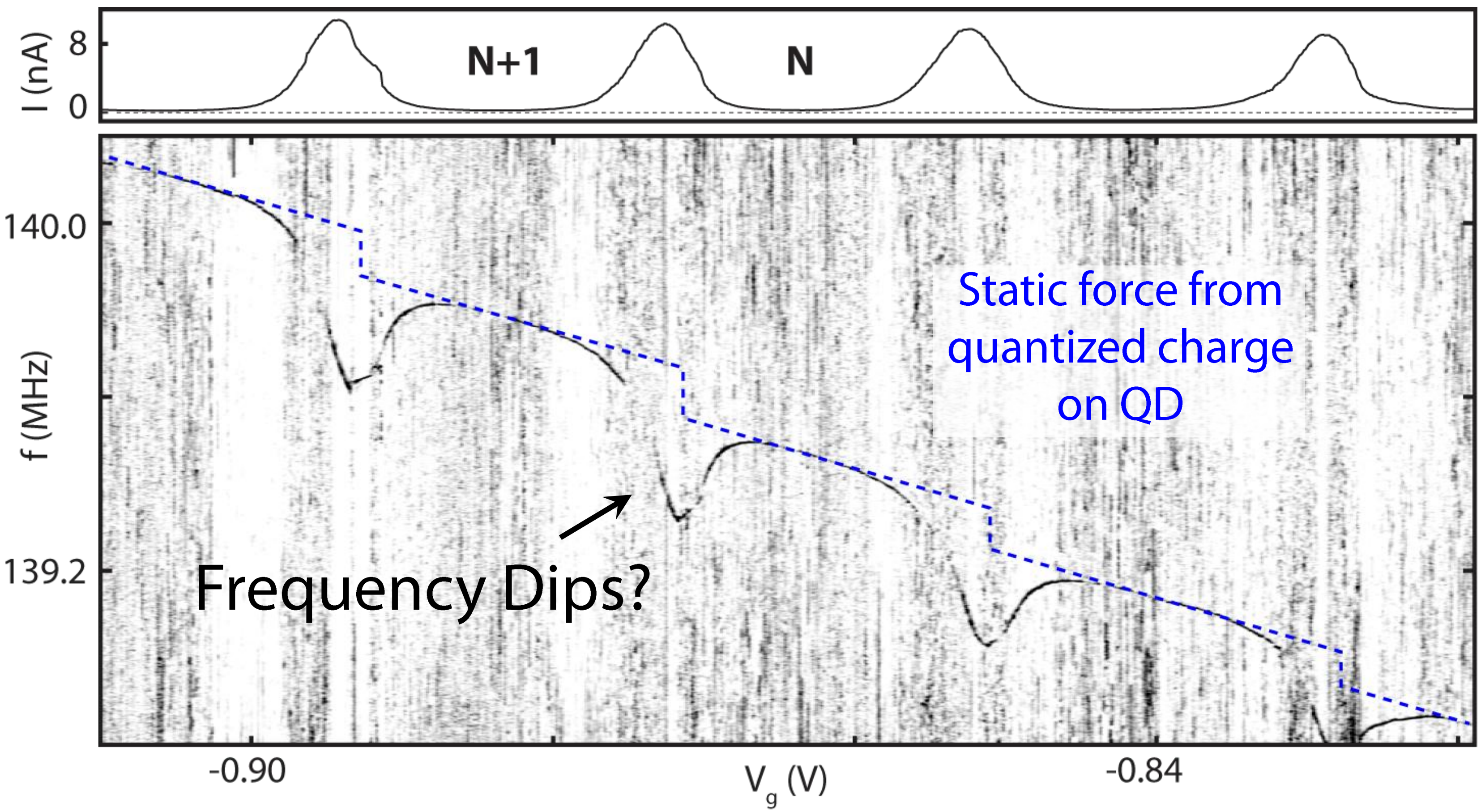


Tuning a Resonator with a Quantum Dot



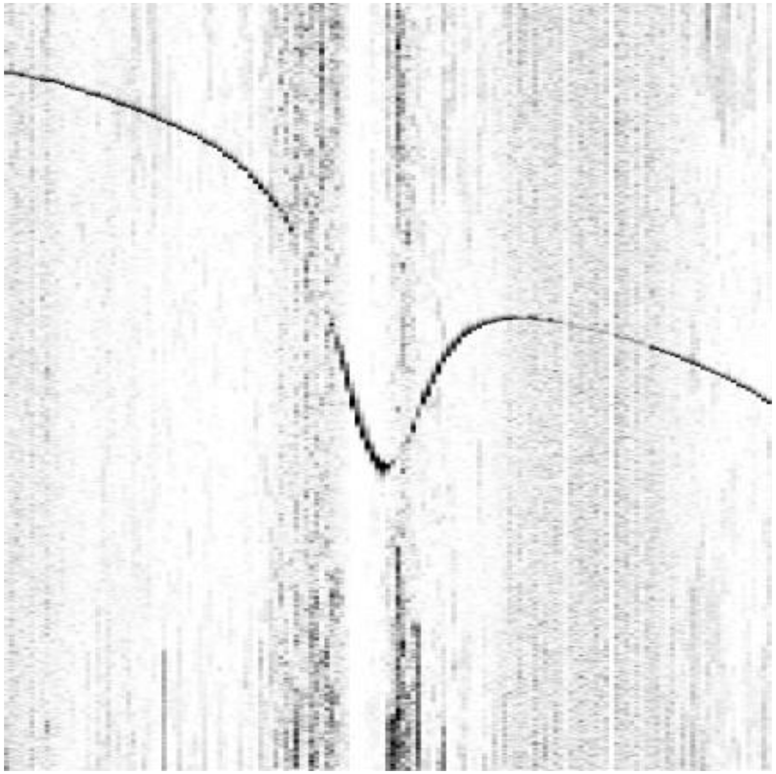
Quantized charge on quantum dot → Steps in resonance frequency

Tuning a Resonator with a Quantum Dot

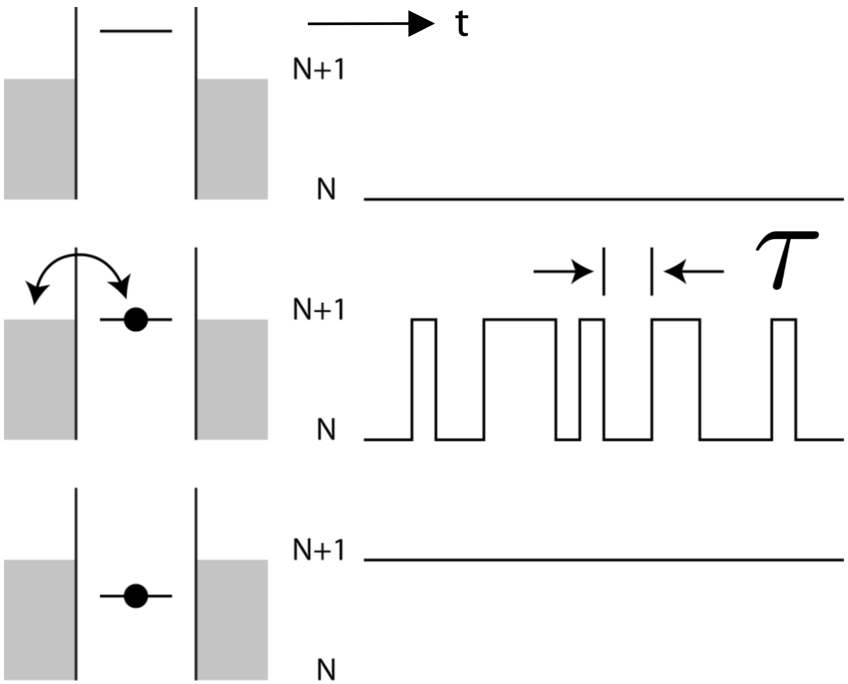


Dips are strange: go the wrong way?

Dips: Dynamic Force from Charge Fluctuations

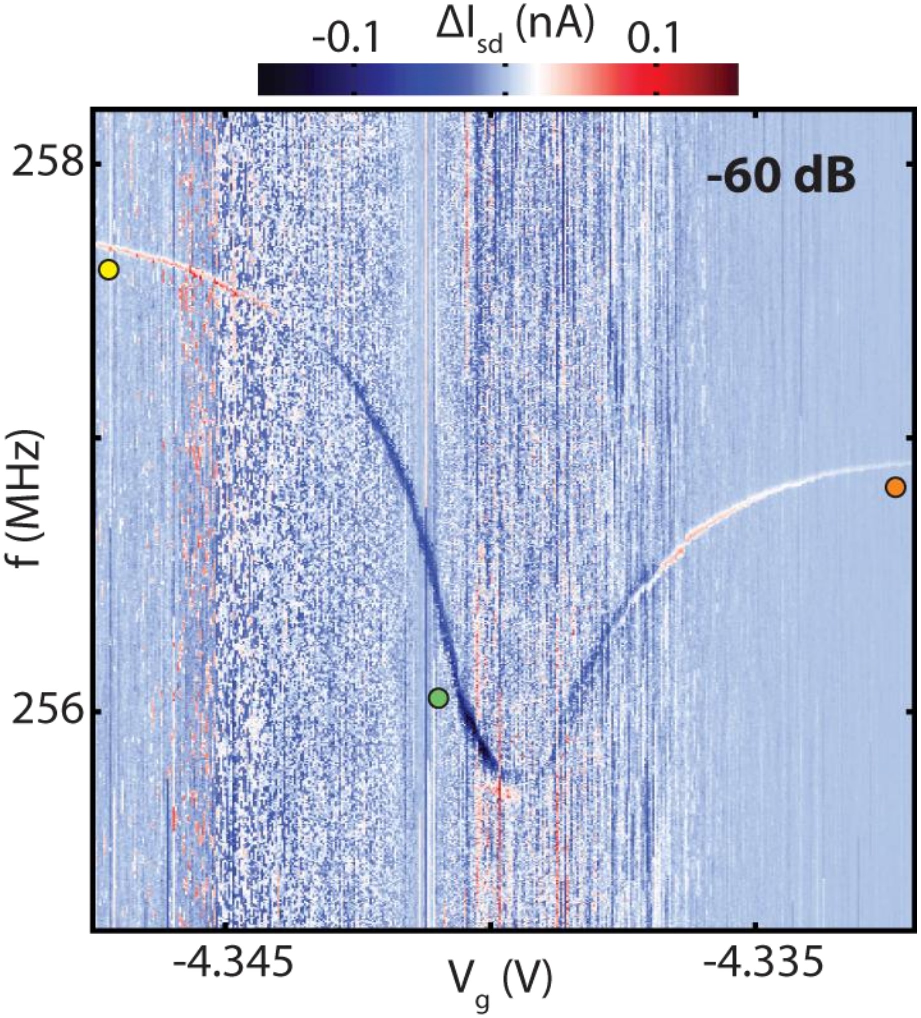


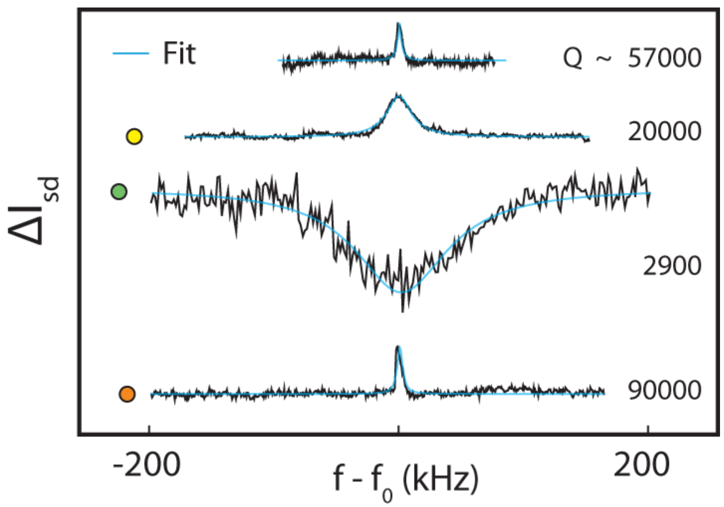
Charge fluctuations:

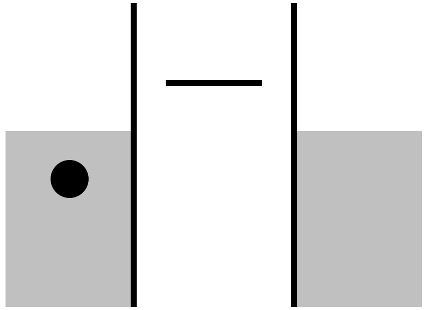


$\omega_{mech} \ll 1/\tau \longrightarrow$ Changes electrostatic part of spring constant ("overscreening" by QD)

Single Electron Damping

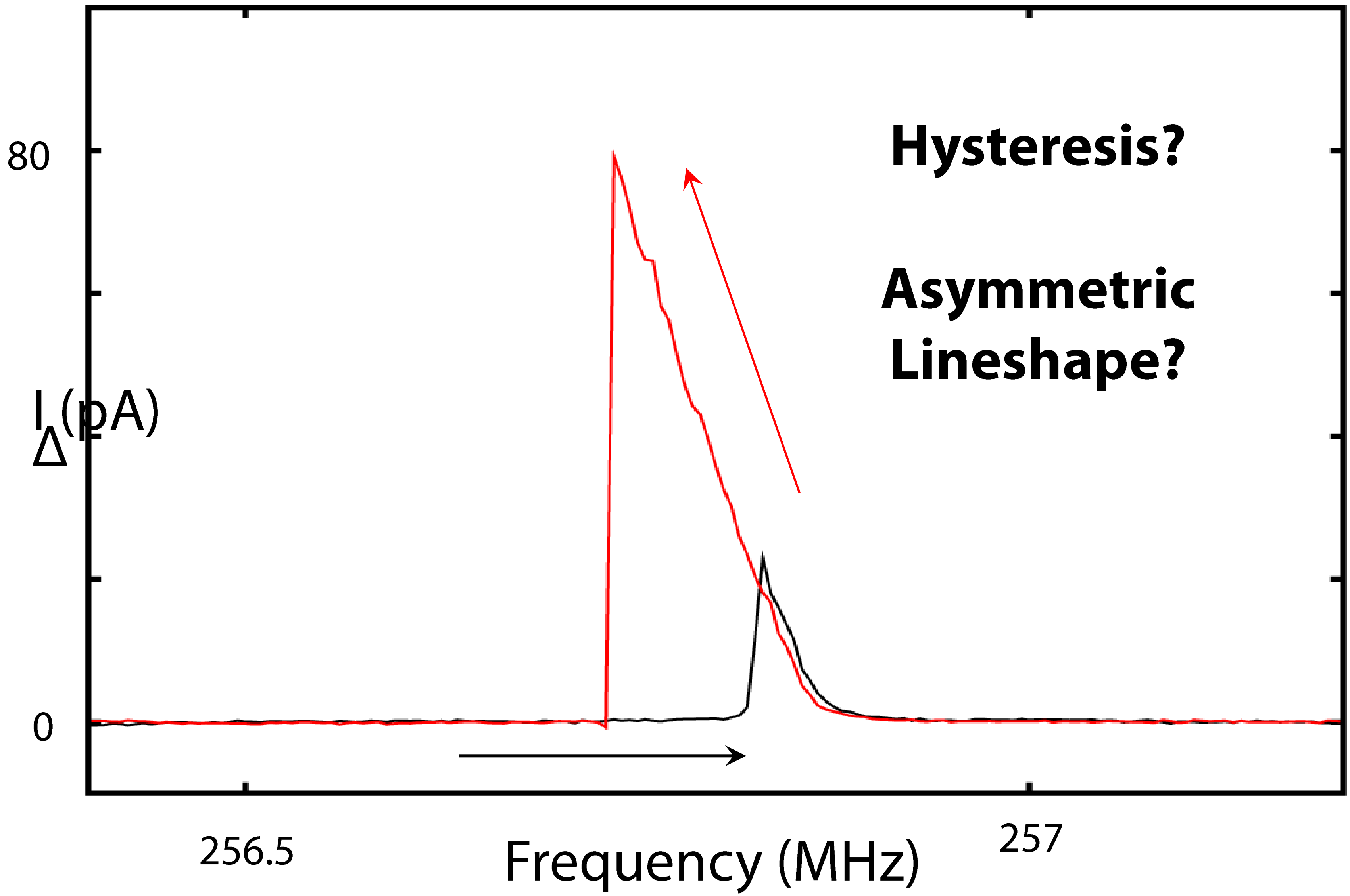






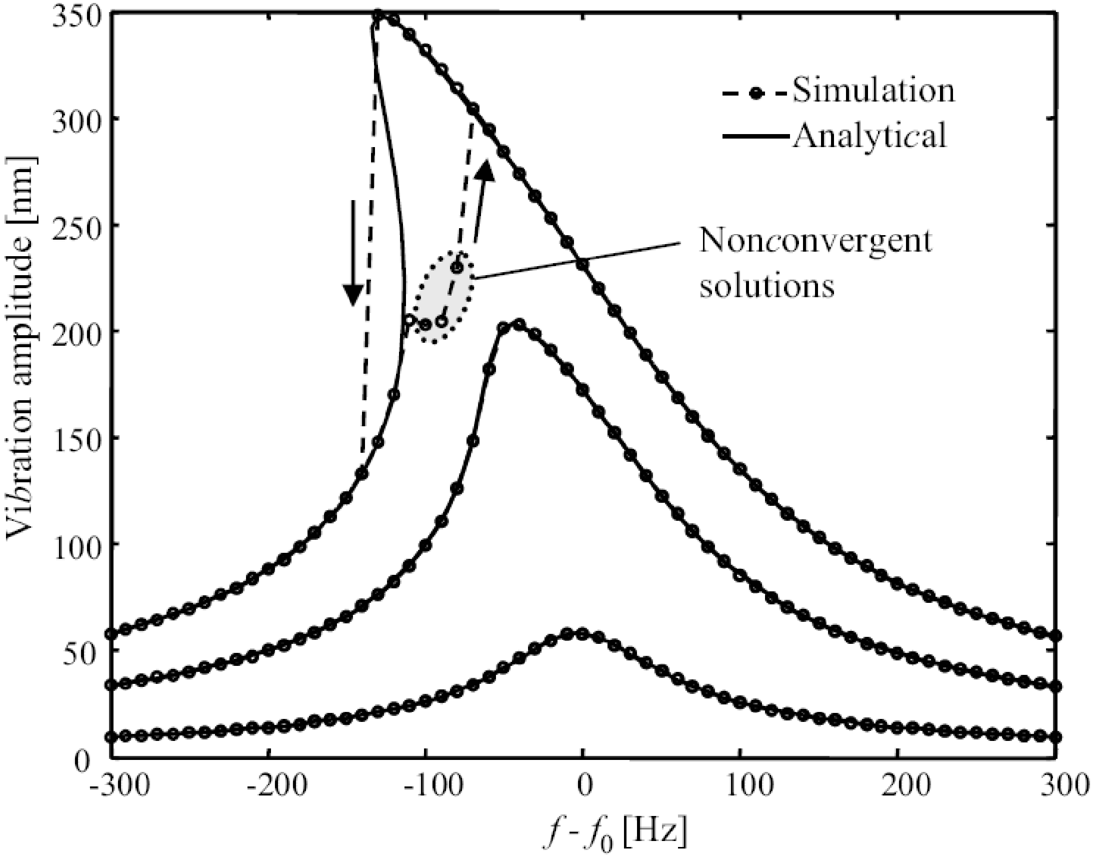
Electrostatic energy gain during tunnelling

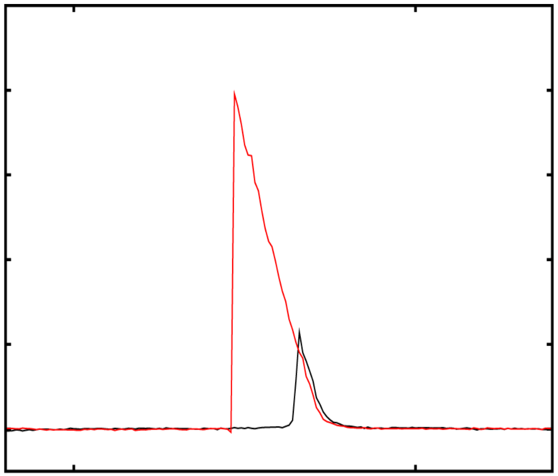
Higher driving power



Line shape at higher power

$$-kx \rightarrow -(k + \alpha x^2)x$$





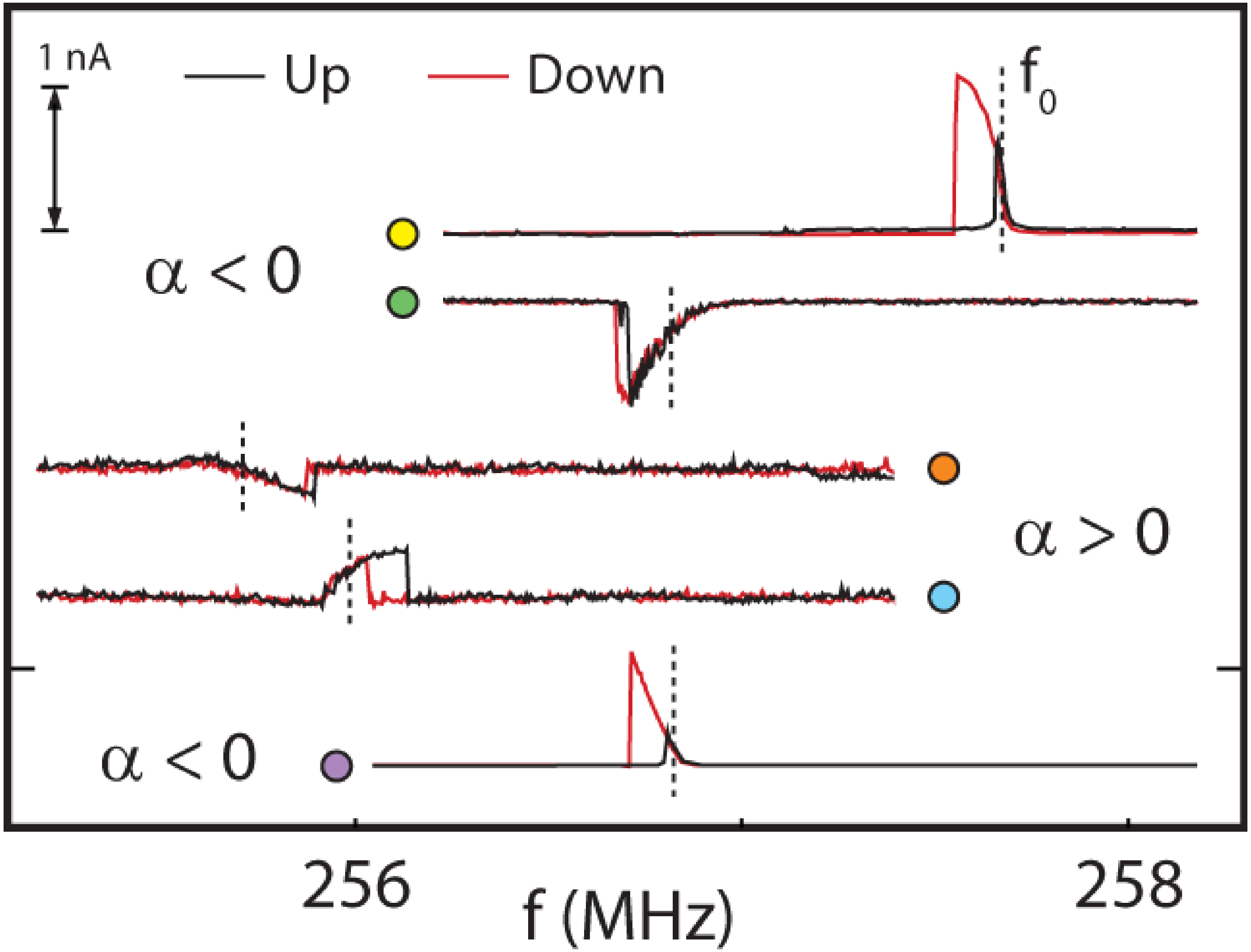
$\alpha < 0$

"softening spring"

$\alpha > 0$

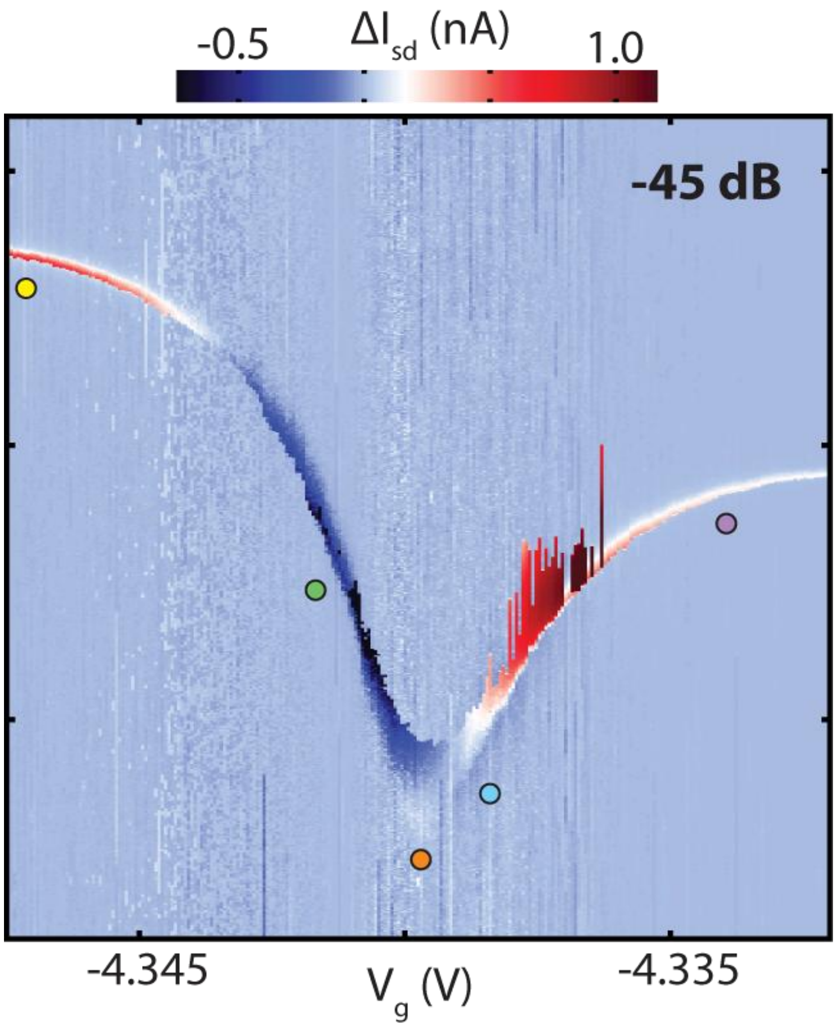
"hardening spring"

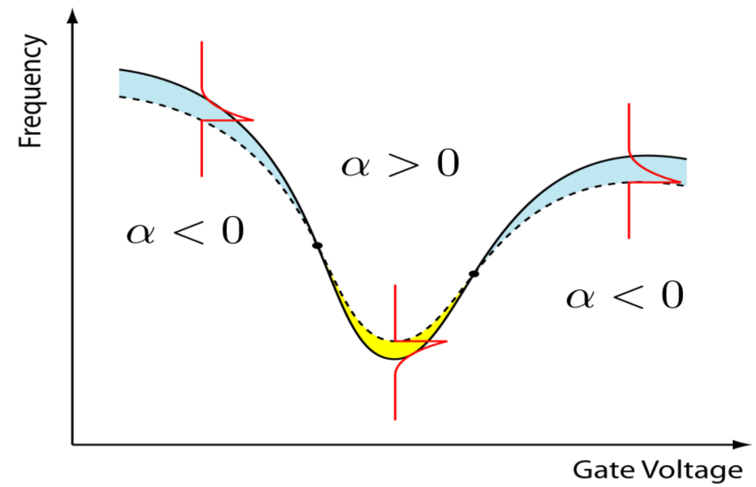
Sign of α changes?

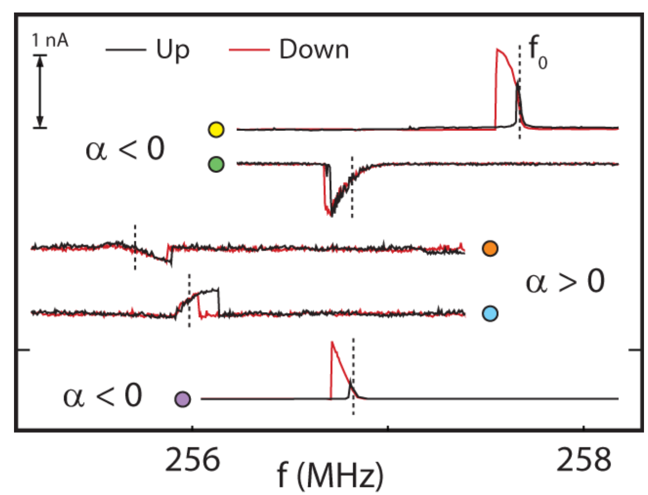


ΔV_g ~ few mV

Quantum Dot Induced Non-Linearity

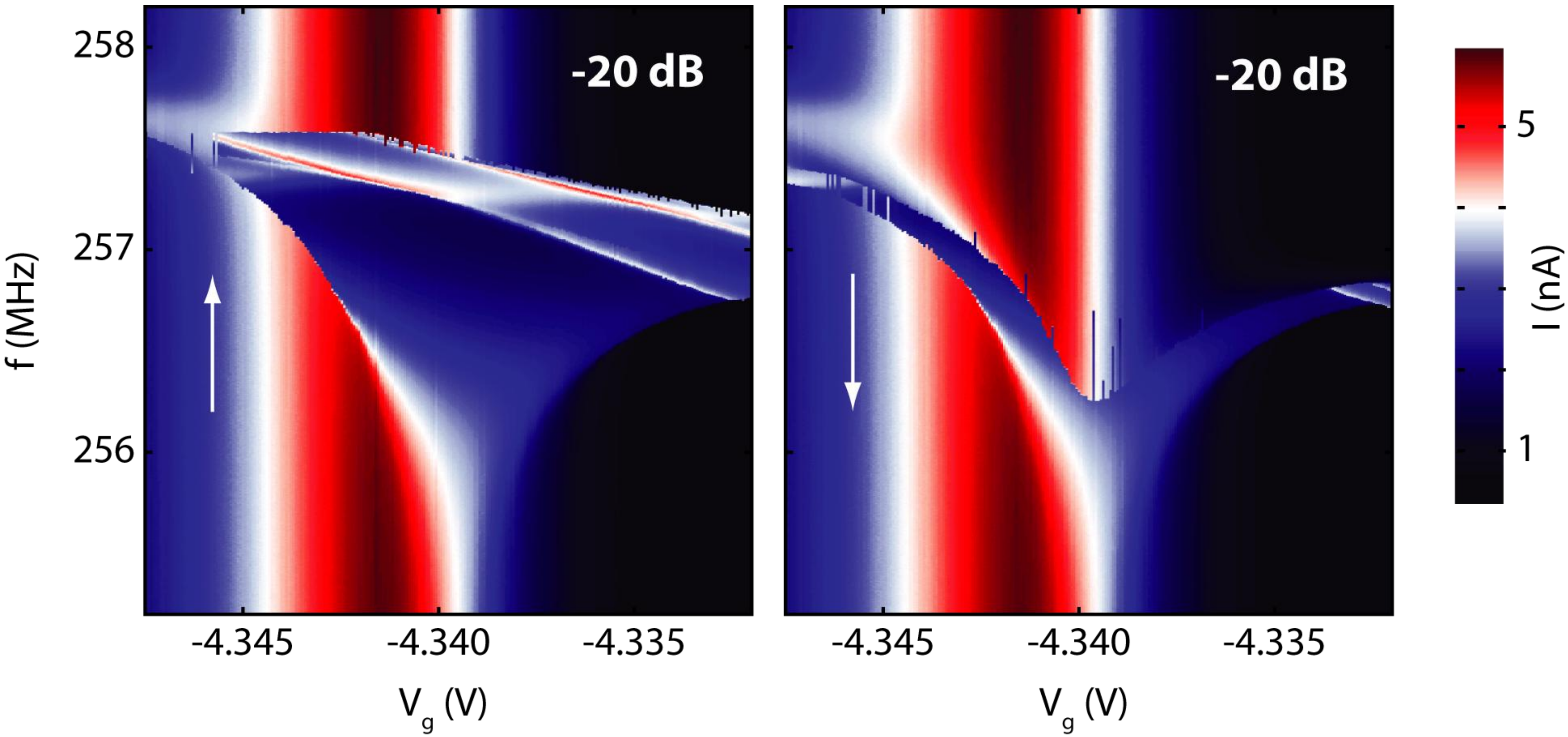






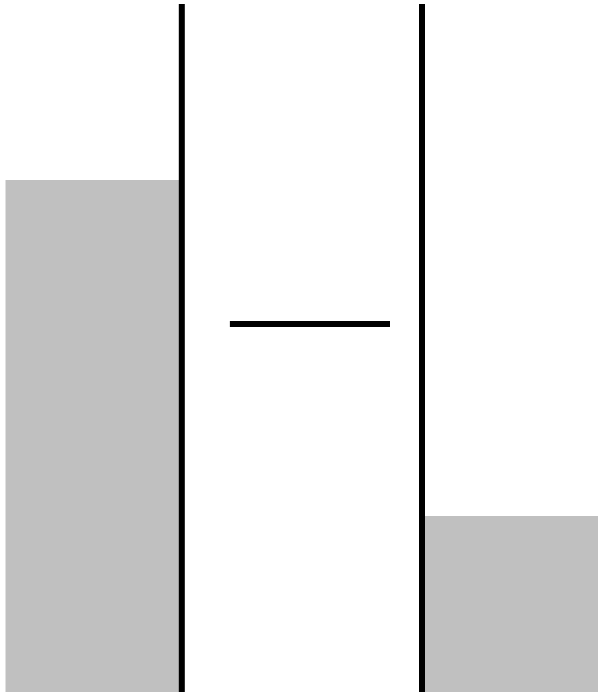
Quantum dot *causes* the non-linearity

Higher powers…



Synchronous pumping of electrical current by mechanical motion?

Turn off the RF driving



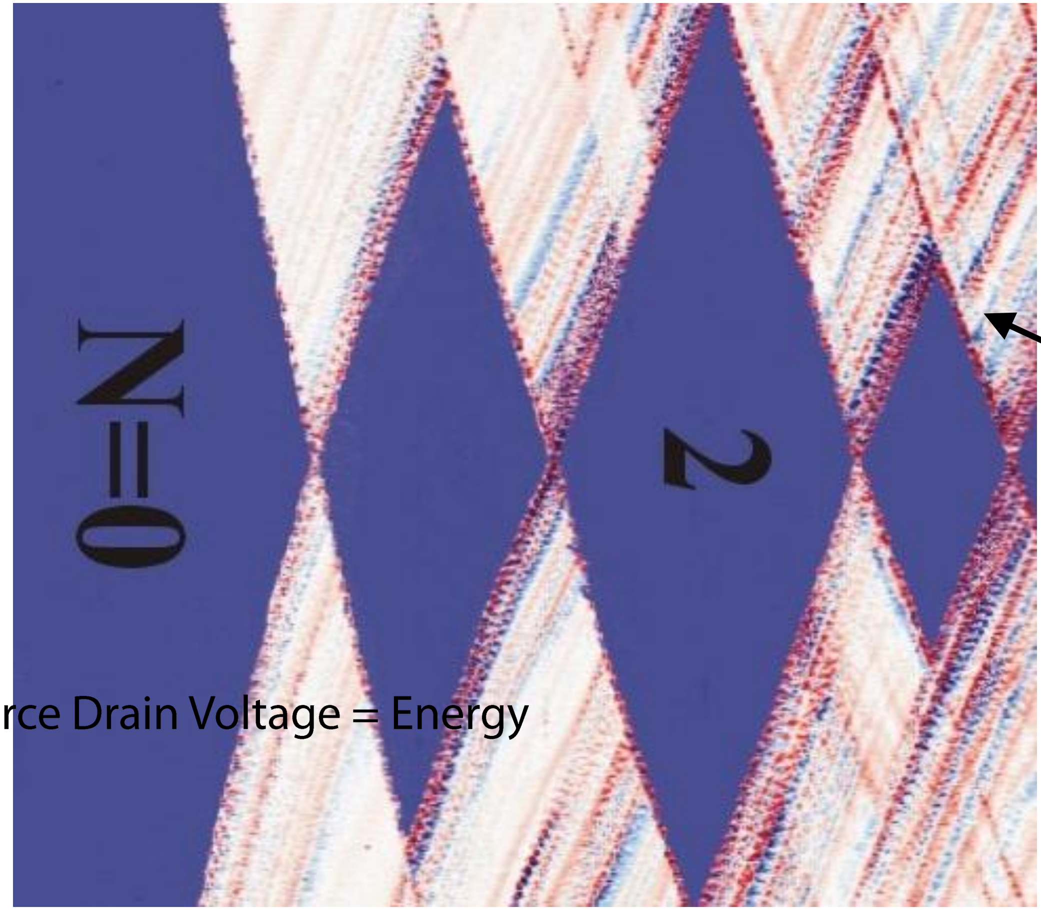
Turn off RF

but

Apply a DC bias across the dot…

A normal quantum dot

Coulomb Diamonds



Source Drain Voltage = Energy

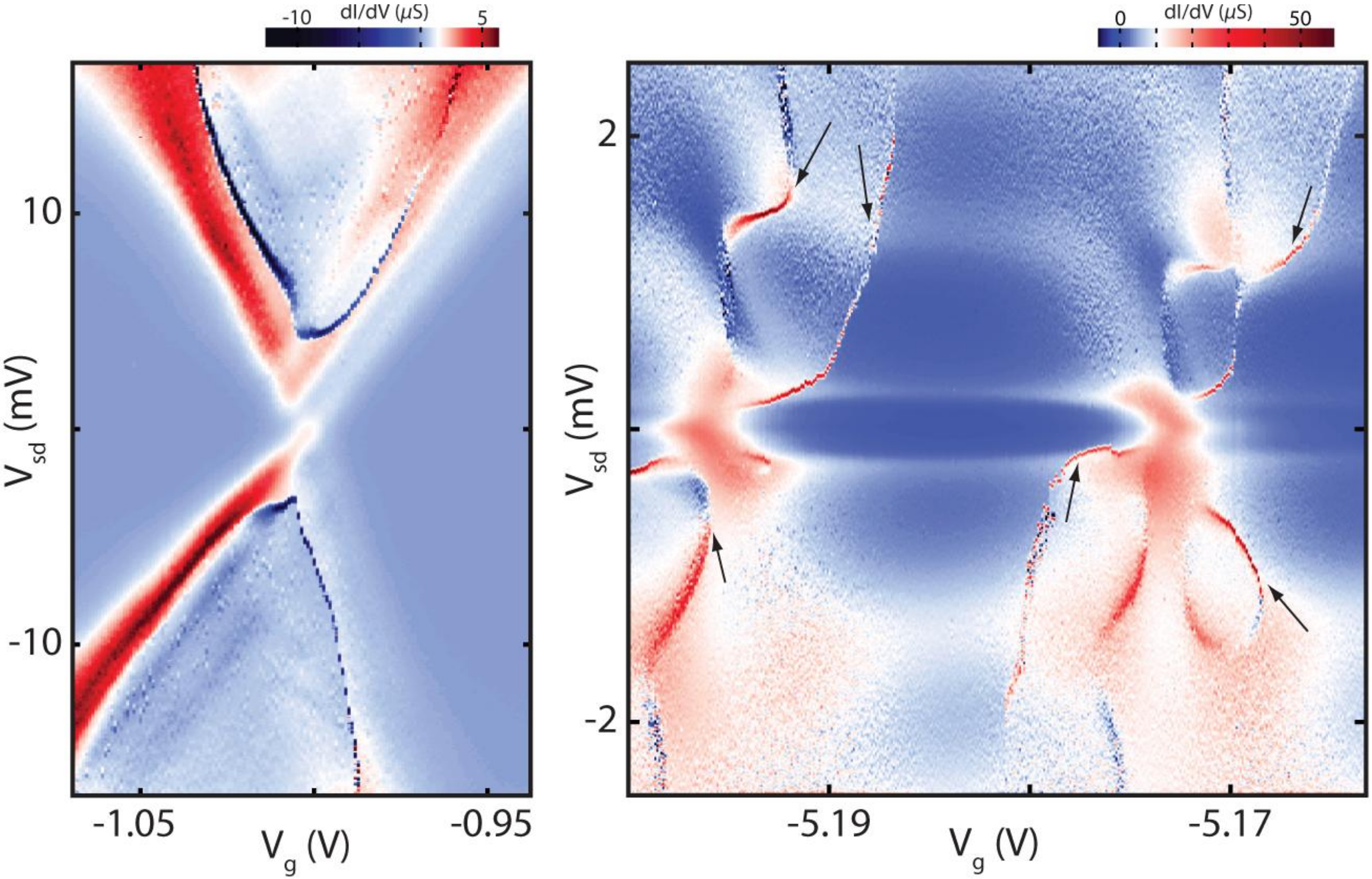
Gate Voltage

Differential conductance (dI/dV)

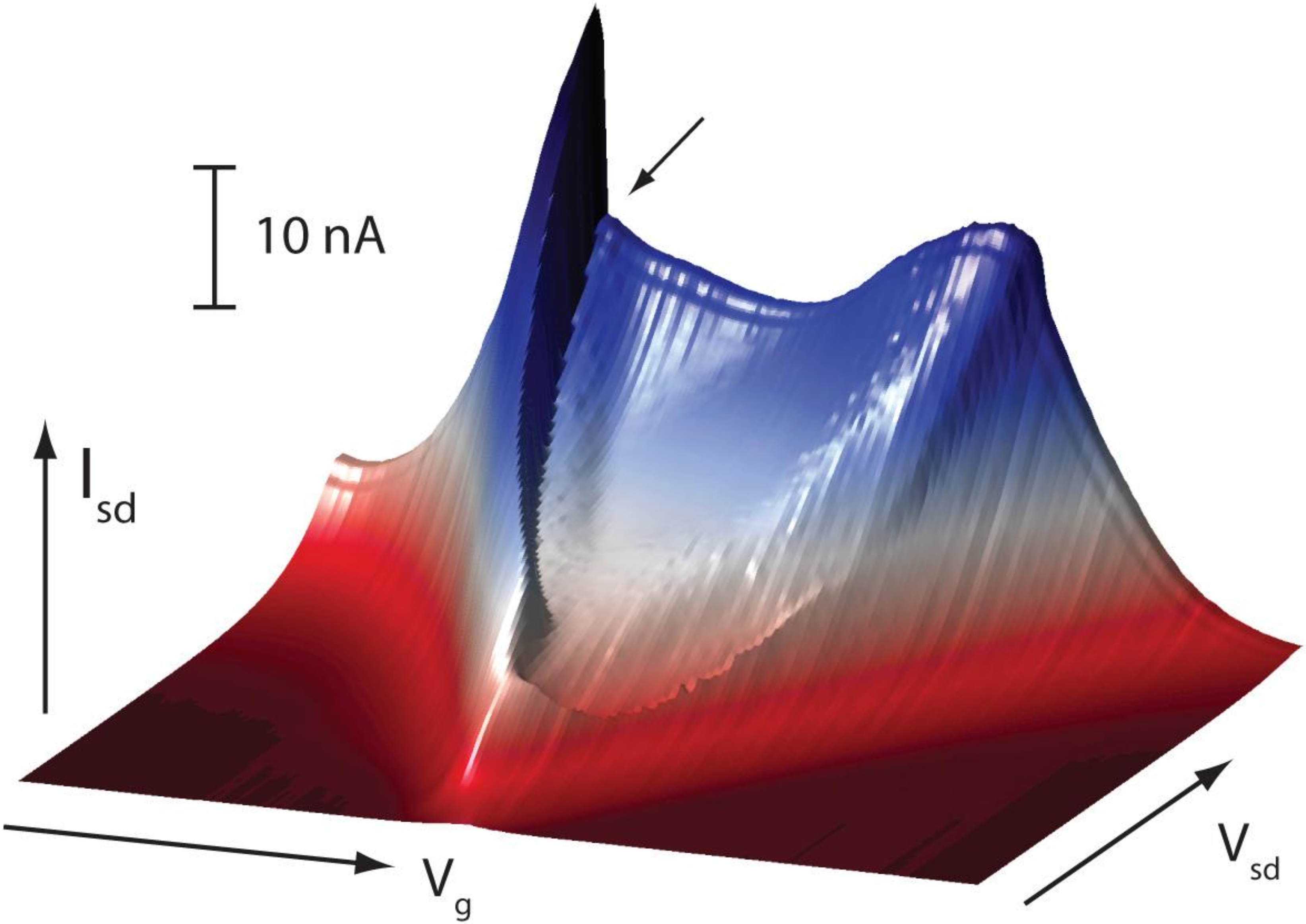
Energy levels in the quantum dot

Quantized level spacing, Zeeman energy, Orbital energies, …

What does our quantum dot look like?



What is this? Could it be mechanical?



Positive feedback mechanism

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Strong feedback and current noise in nanoelectromechanical systems

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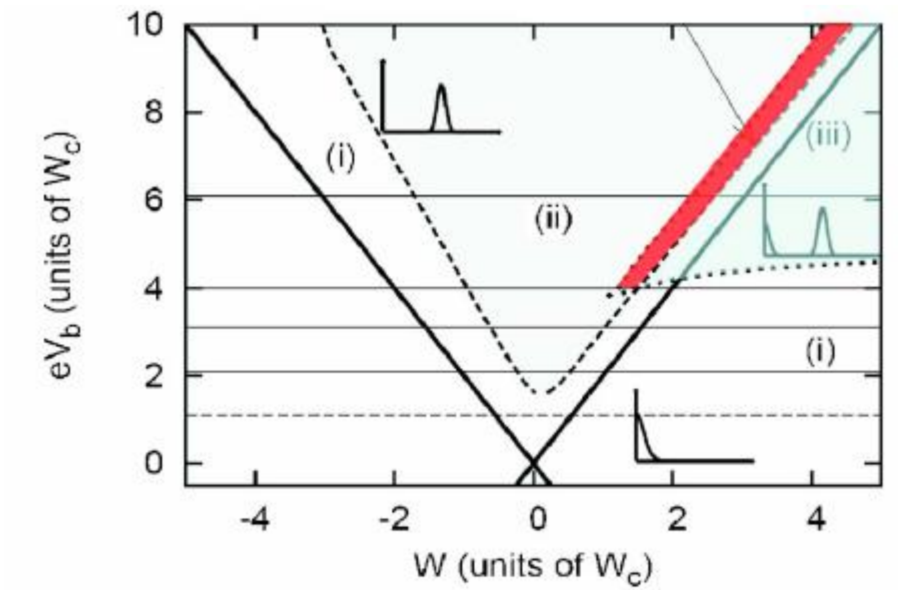
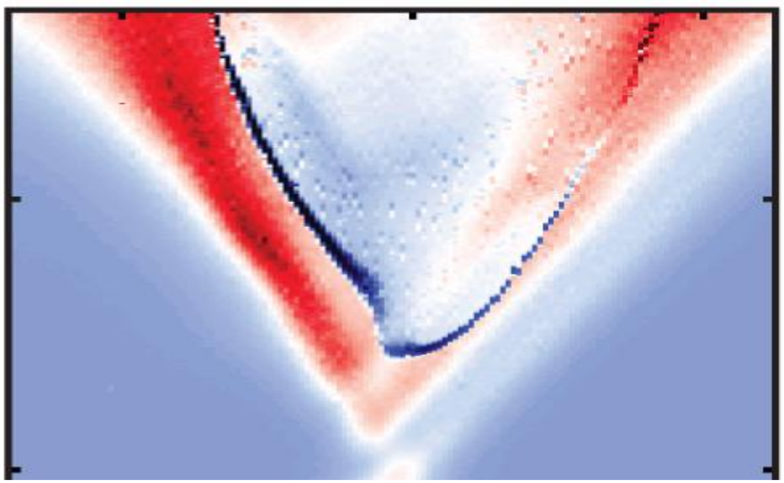
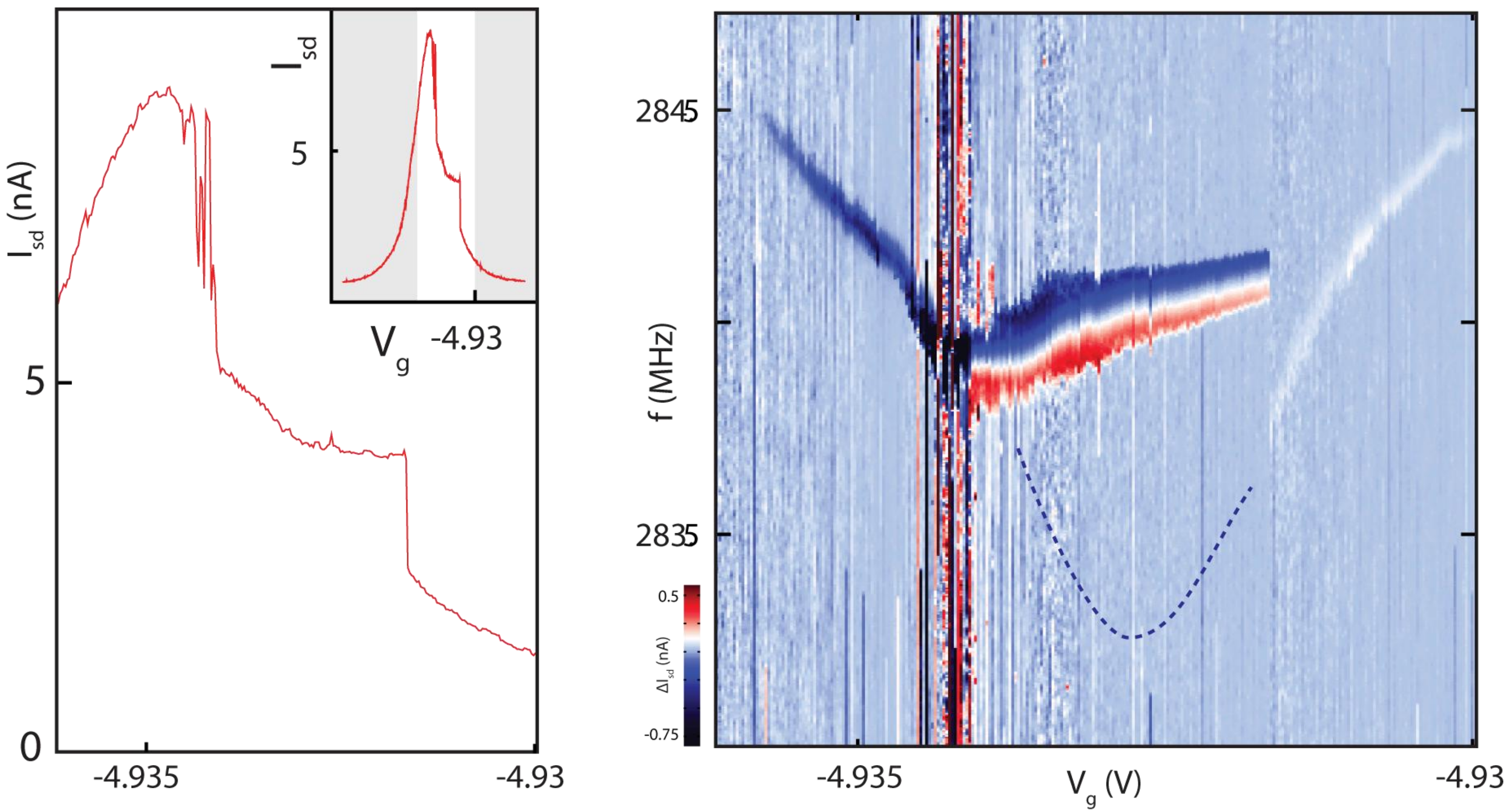
(Received 8 March 2006; revised manuscript received 16 February 2007; published 10 May 2007)





Need: $\Gamma \gg \omega$ and $Q \gg 1$

Mechanical Signature



"Spontaneous driving of mechanical resonator by single electrons"

A Quantum Nanomechanical Resonator

Q	150,000	80,000
Mass	10^{-21} kg	10^{-21} kg
Frequency	500 MHz	**2.8 GHz**
$\bar{n}$ @ 100 mK	**9.5**	**~0**
Δx_{ZPF}	**~5 pm**	

Try to do something quantum…

Summary

Clean carbon nanotubes: a new breed

A cool platform for making quantum dot devices

High Q-factor mechanical resonators

Single electrons coupling to nanomechanical motion

A quantum future?