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Coupling of electronic and mechanical degrees of freedom in quantum nanostructures

Renaud Leturcq

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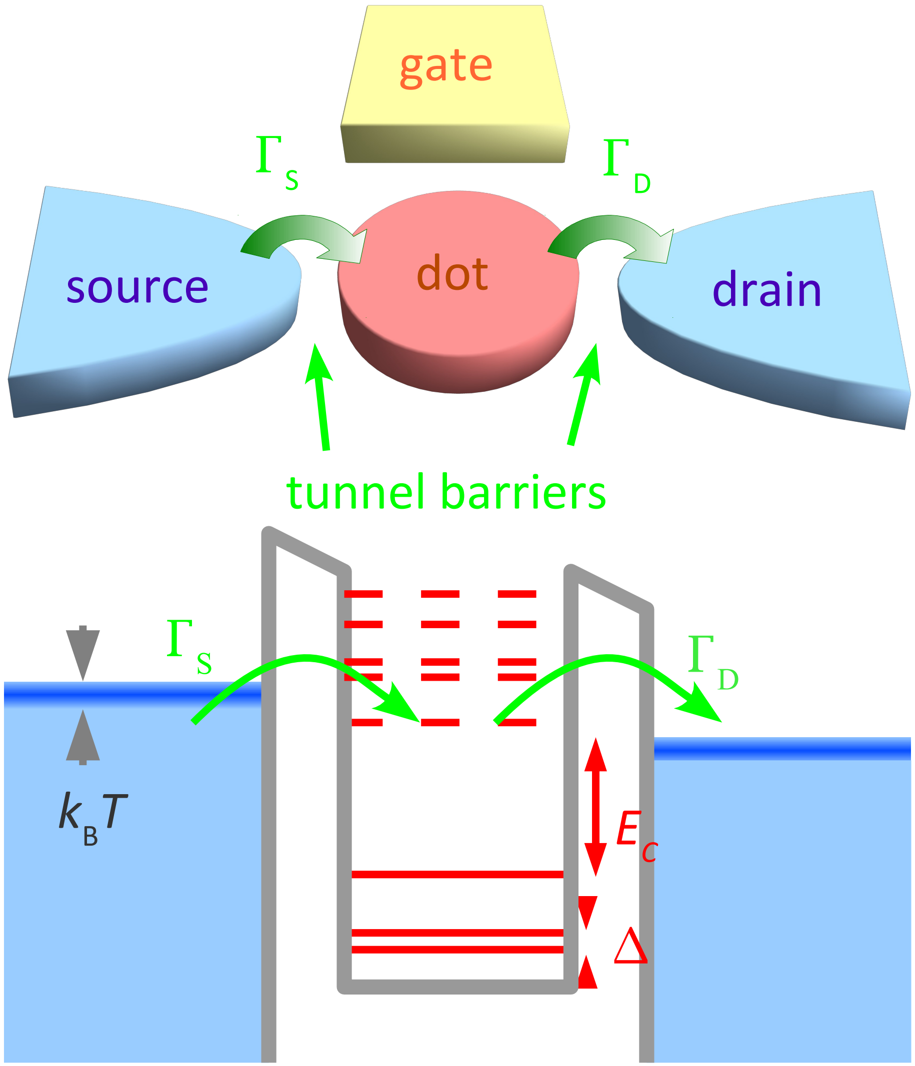
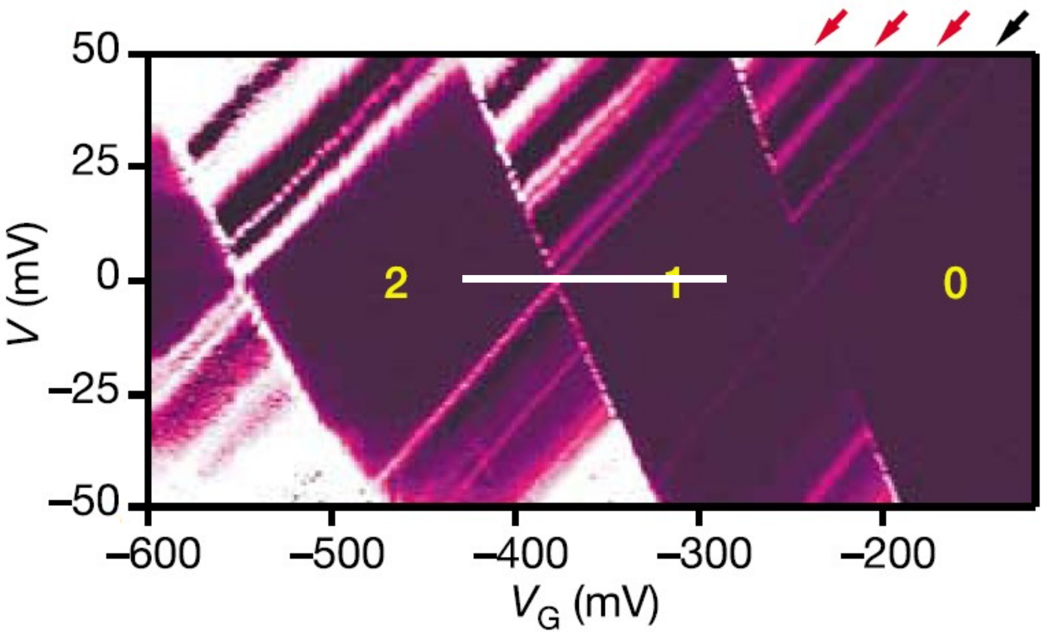
Summary

- Part 1: Electronic transport in quantum nanostructures
  - Quantum effects can be observed on electronic transport for a sufficiently small size and at low temperature!
  - In these conditions, electronic properties of small nanostructures ressemble those of artificial atomes or molecules (quantum dots)

Electronic spectroscopy in quantum dots

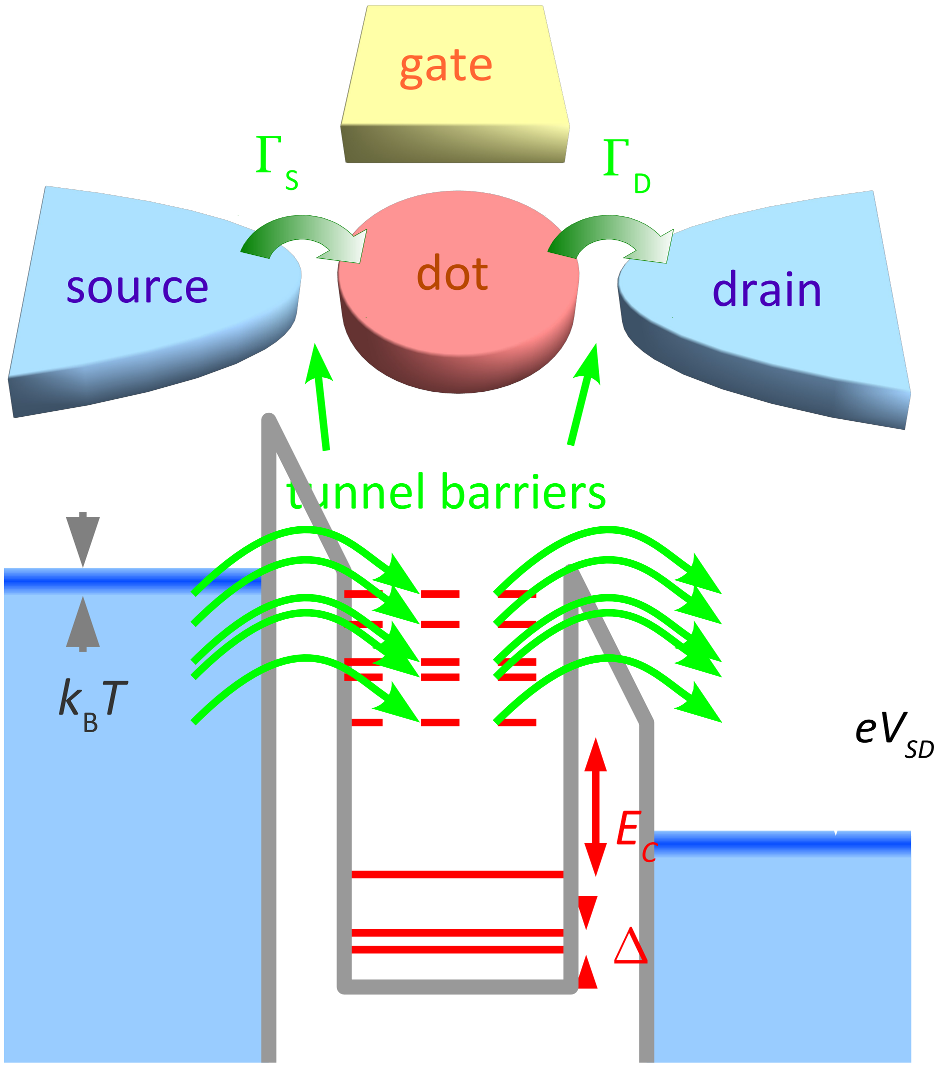


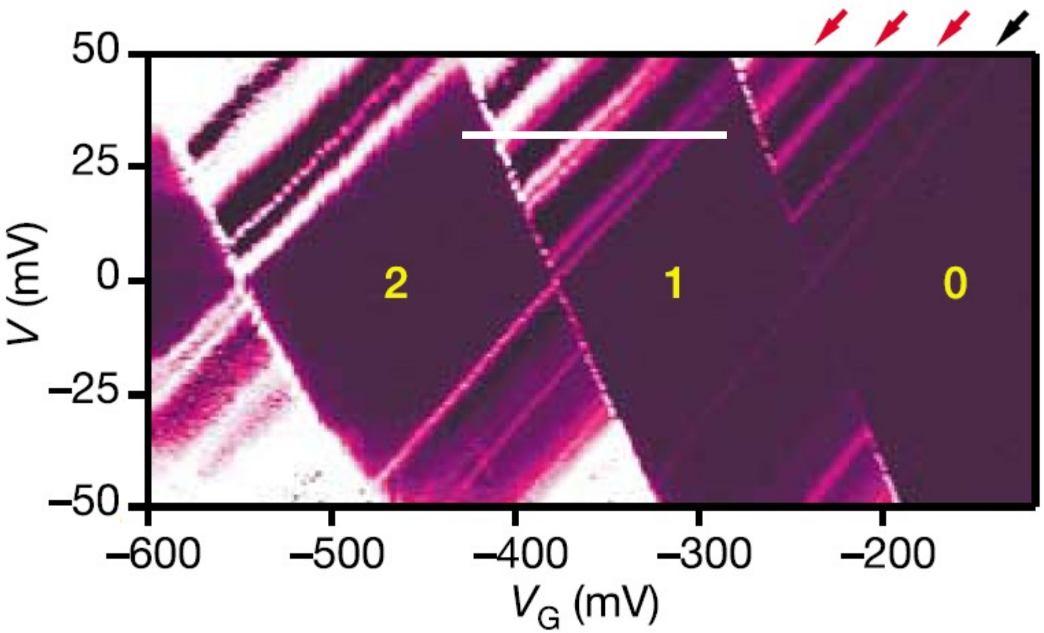


P. Jarillo-Herrero *et al.*, Nature **429**, 389 (2004)

quantum dots <=> artificial atoms or molecules

Electronic spectroscopy in quantum dots





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Summary

- Part 1: Electronic transport in quantum nanostructures
  - Quantum effects on electronic transport: or a sufficiently small size and at low temperature!
  - In these conditions, electronic properties of small nanostructures ressemble those of artificial atomes or molecules
- Part 2: Coupling of electrical and mechanical degrees of freedom
  - Real molecules have a vibrational spectrum... what about artifical atoms/molecules?
  - Can one observe quantum effects on the mechanical degree of freedom of nanostructures?

Outline

- Part 1: Electronic transport in quantum nanostructures
- Part 2: Coupling of electrical an mechanical degrees of freedom
  - Energy and length scales of a mechanical system
  - Fabrication of nanoelectromechanical systems (NEMS)
  - Exemple: Vibrational spectroscopy of suspended quantum dots

Energy and length scales of a mechanical system

Energy scale of a vibrating structure

- Vibrating mode fundamental frequency: f_m
  - flexural mode of a cantilever of length *l*, width *w*, thickness *t*, mass density *ρ* and Young's modulus *E*

$$f_m = 0.56 \frac{t}{l^2} \sqrt{\frac{E}{12\rho}}$$

  - Si cantilever ($E = 1.5\ 10^{11}$ N.m^{-2}, $\rho = 2.33\ 10^{3}$ kg.m^{-3})
    $l = 1$ um, $t = 0.1$ um $\Rightarrow f_m = 130$ MHz
- Rule for observing quantum behavior: $hf_m > k_B T$
  - Si cantilever (see above) $\Rightarrow T < 6$ mK
  - more favorable in strong and light materials

Length scale of a vibrating structure

- Zero-point displacement uncertainty in the fundamental mode, Δx_{ZP}

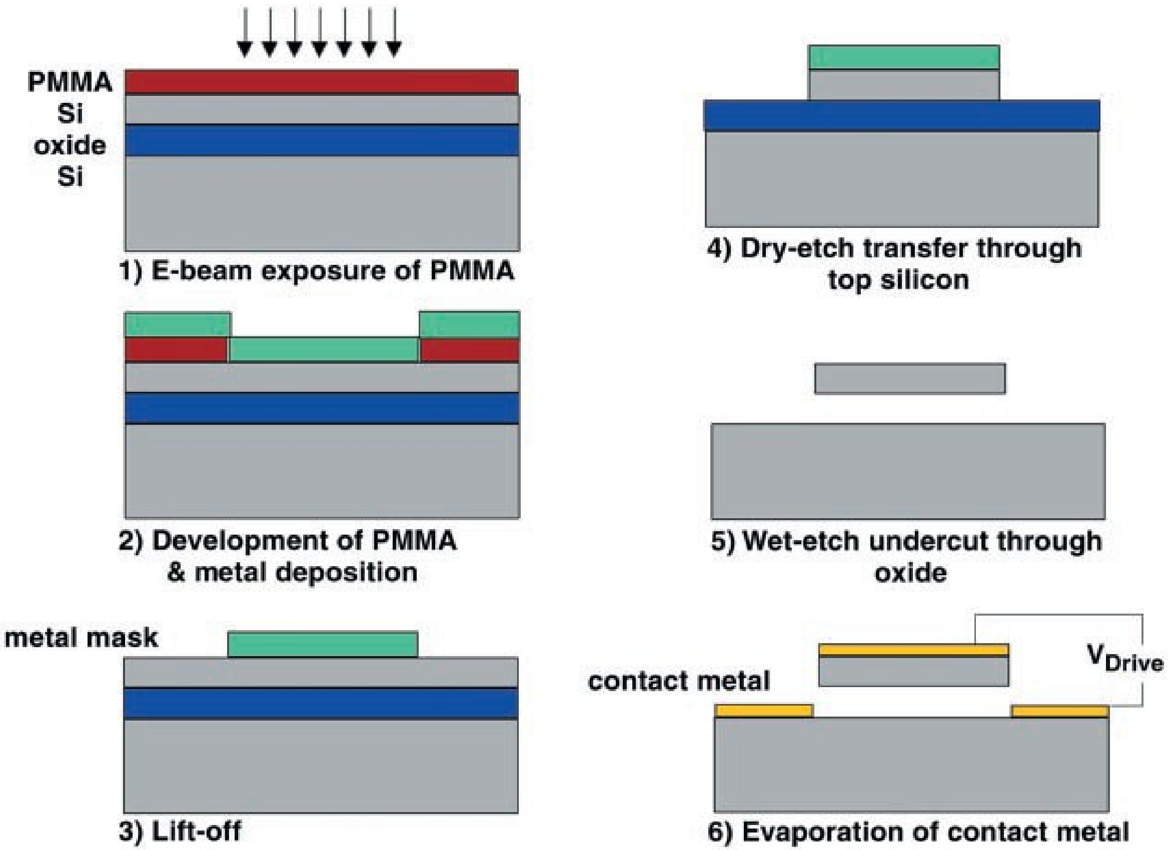
$$\Delta x_{ZP} = \sqrt{\frac{\hbar}{2 m_{eff} \omega_m}}$$

  - Si cantilever (see above) ⇒ $\Delta x_{ZP} \approx 10^{-3}$ Å

- Detection of very small displacements possible in nanostructures
  - optical methods (interferometry)
  - electrical methods (capacitive, inductive, magnetic field, etc...)
  - indirect method: coupling of electronic and mechanical degree of freedom

Fabrication of suspended nanostructures

- Most commonly used for MEMS and NEMS: etching of a sacrificial layer



H. G. Craighead, Science **290**, 1532 (2000)

Fabrication of suspended nanostructures

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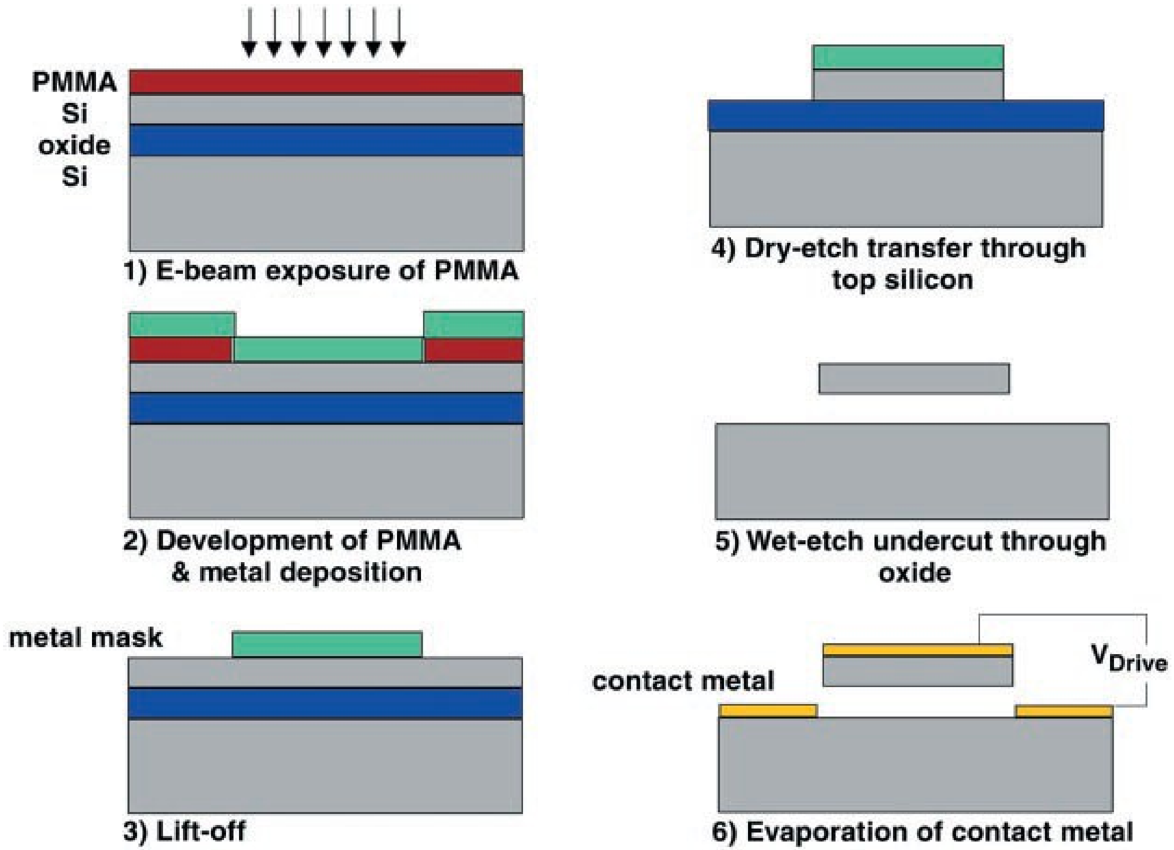
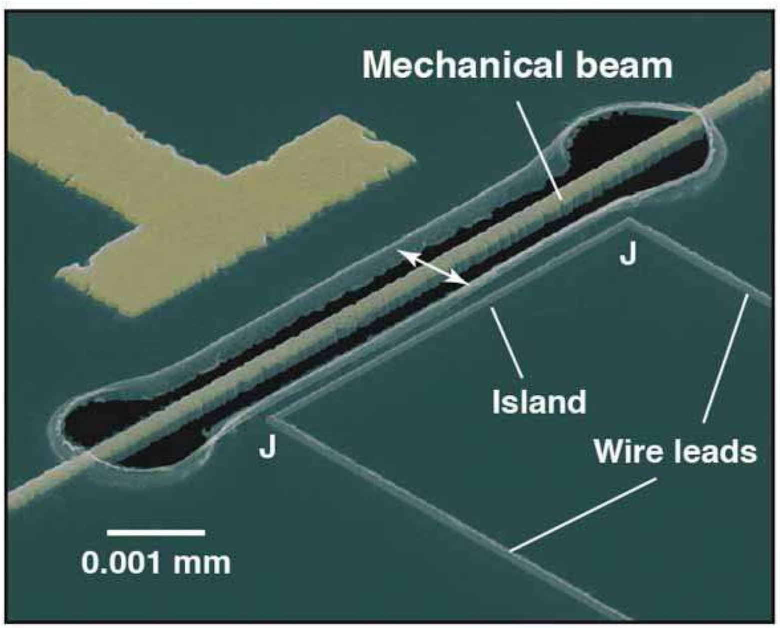


H. G. Craighead, Science **290**, 1532 (2000)

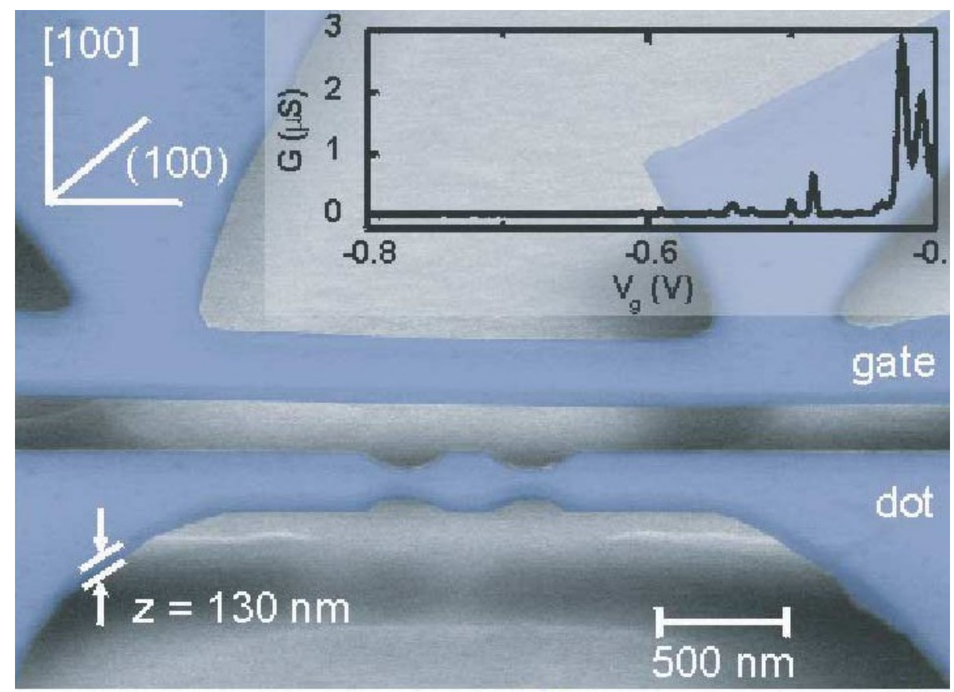
Fabrication of suspended nanostructures

- Doubly clamped SiN beam



M. D. Lahaye *et al.*, Science **304**, 74 (2004)

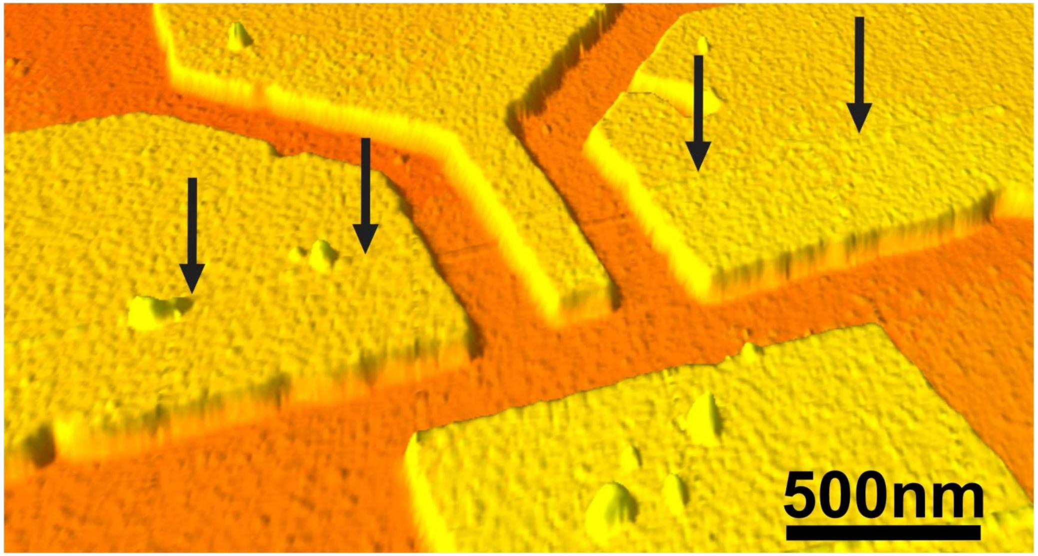
- suspended quantum dot in a GaAs/GaAlAs heterostructure



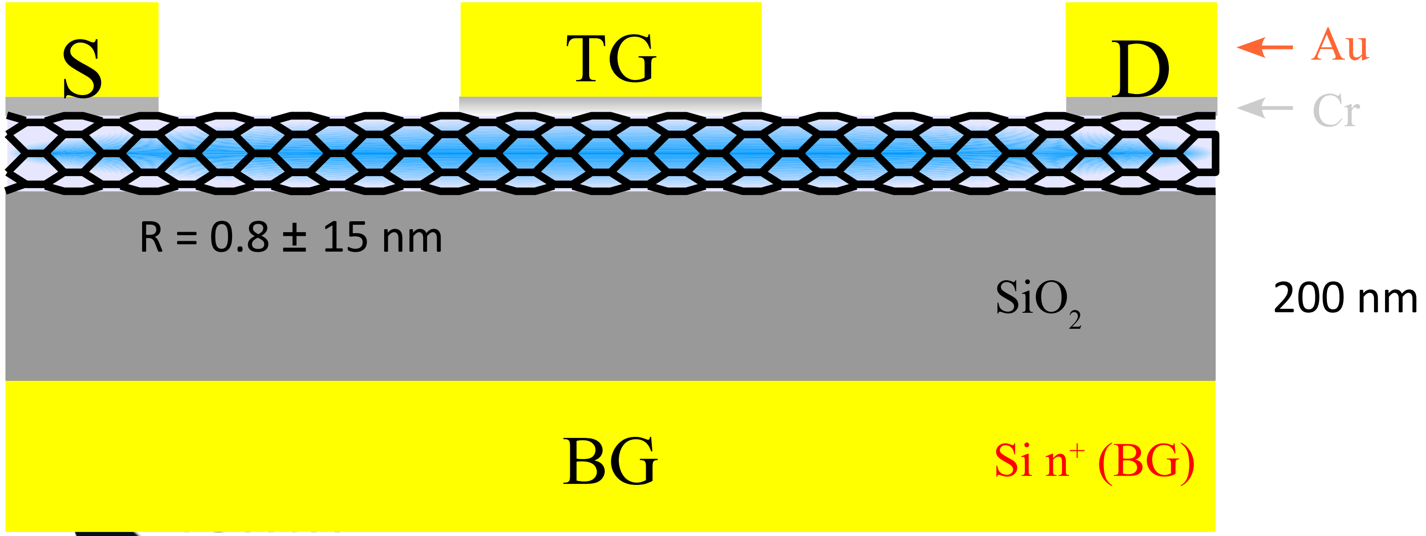
E. M. Weig *et al.*, Phys Rev. Lett. **92**, 046804 (2004)

Combined bottom-up and top-down approaches

- CNT growth
- Cr/Au evaporation

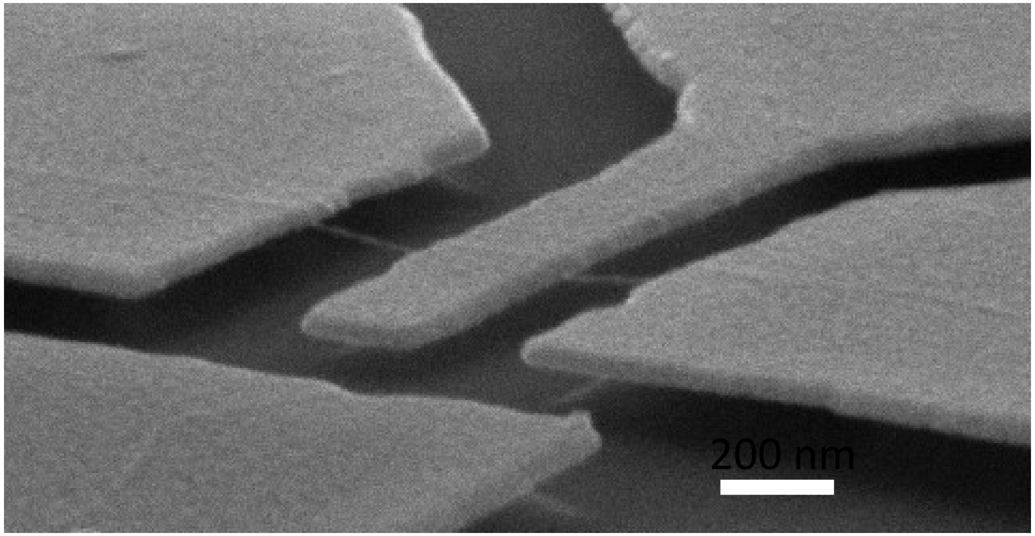


C. Stampfer *et al.*



Combined bottom-up and top-down approaches

- CNT growth
- Cr/Au evaporation
- HF under-etching



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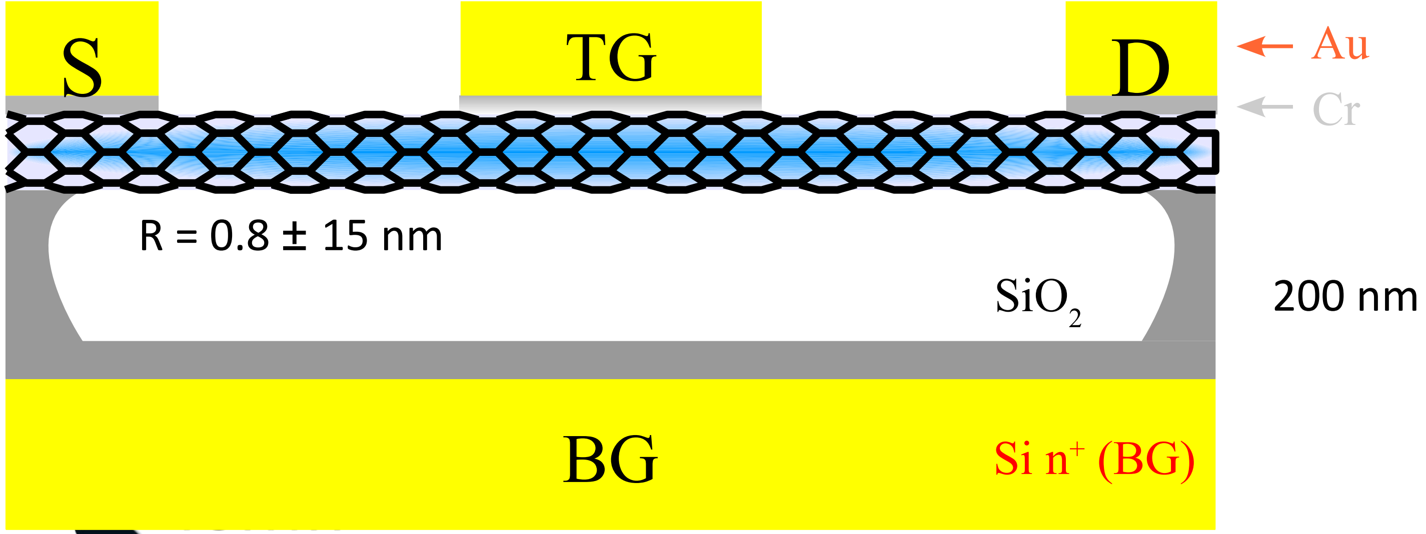
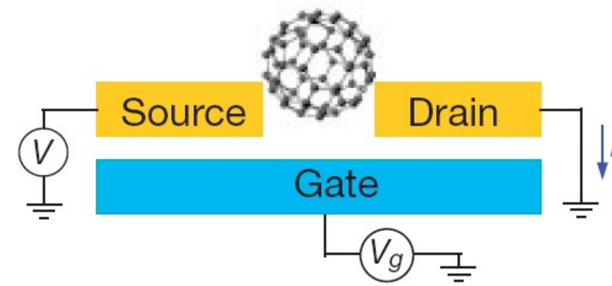
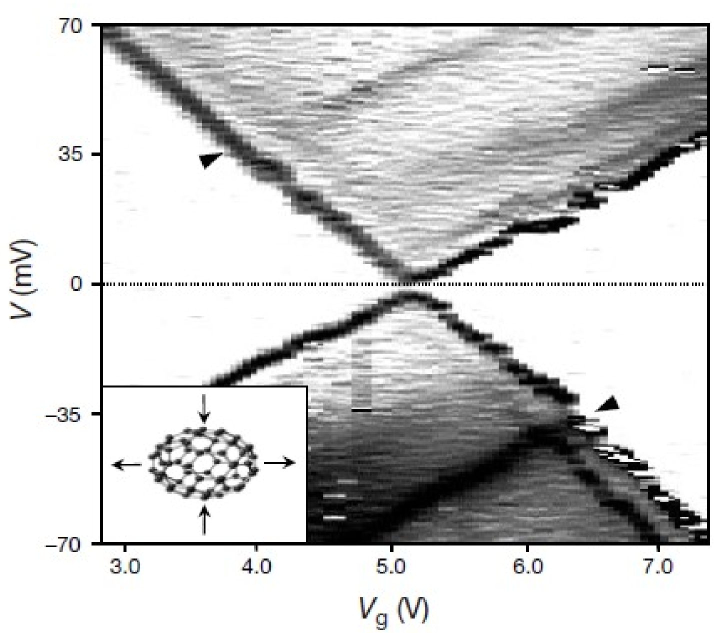


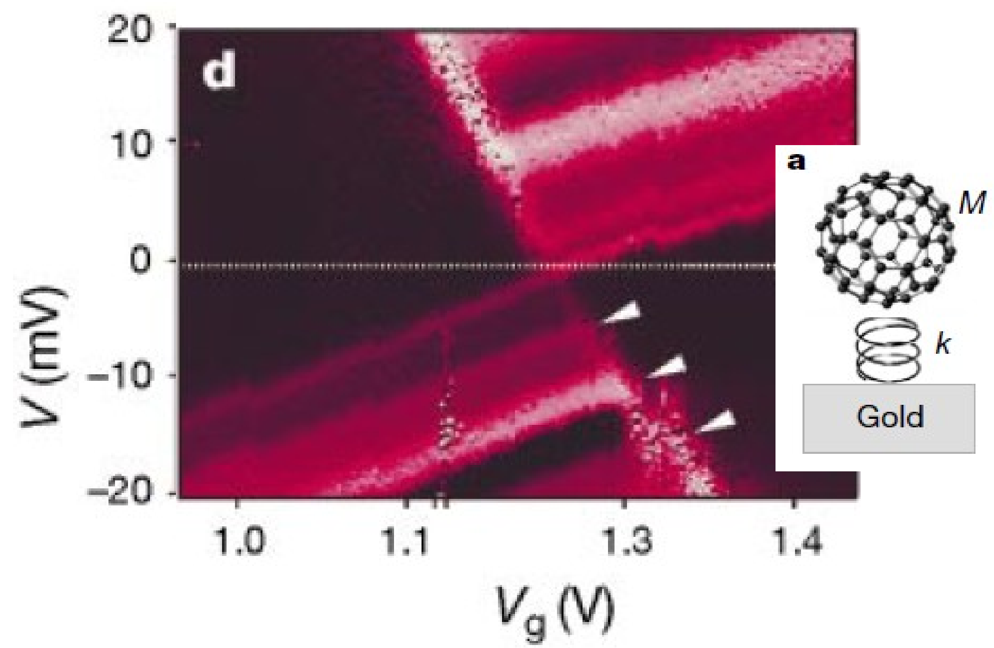
Vibrational spectroscopy of quantum dots

Vibrational excited states in a molecular quantum dot



- Contacted fullerene molecule
  - caracteristic energy scale much lower than the expected electronic excited states ⇒ attributed to vibration modes





H. Park *et al.*, Nature **407**, 57 (2000)

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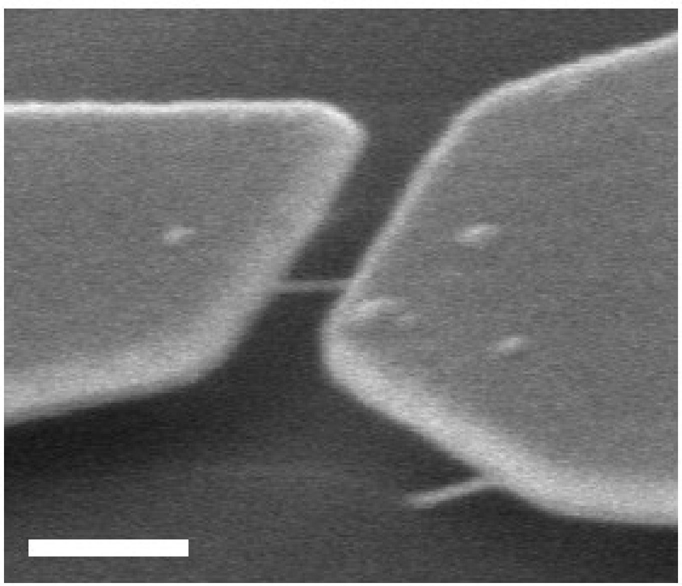
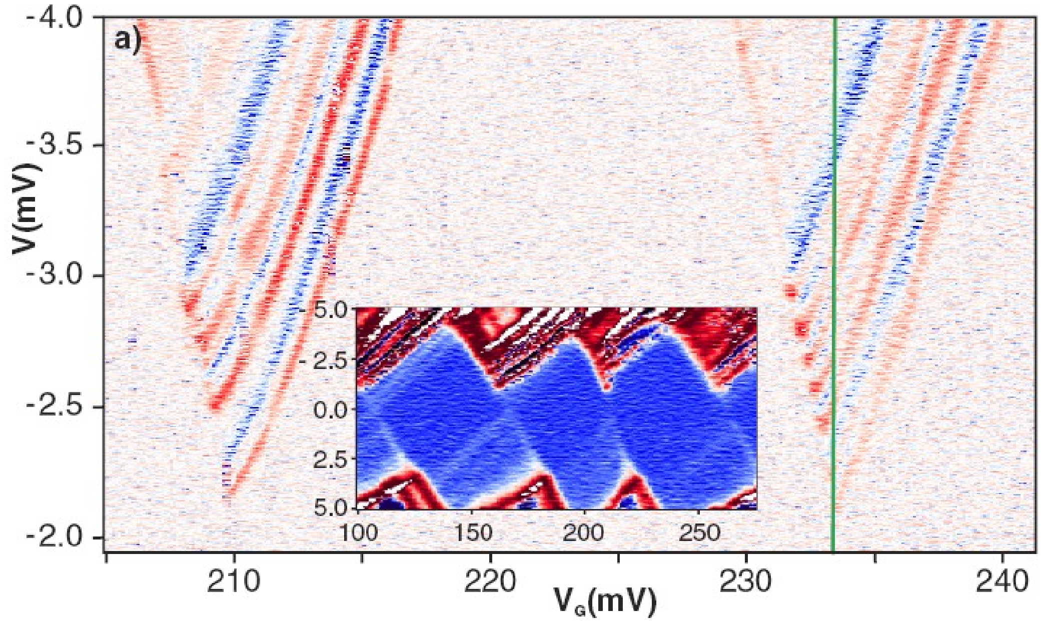
see also: L. H. Yu *et al.*, Phys. Rev. Lett. **93**, 266802 (2004)
A. N. Pasupathy *et al.*, Nano Lett. **5**, 203 (2005)

Vibrational excited states in a carbon nanotube quantum dot

- Suspended carbon nanotube quantum dot



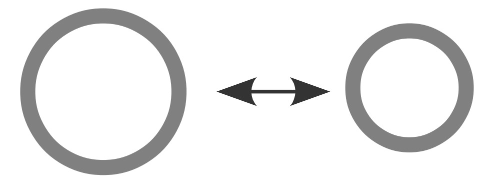


S. Sapmaz *et al.*, Phys. Rev. Lett. **96**, 026801 (2006)

Origin of the vibration in a carbon nanotube

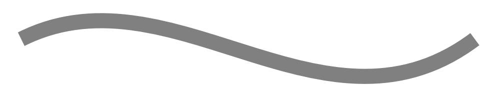
- Radial breathing modes (RBM)

  ΔEvib = 14 meV for r = 1 nm

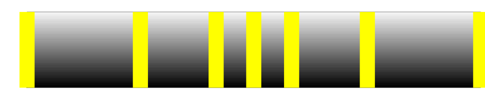


- Bending modes

  ΔEvib = 0.4 μeV for r = 1 nm and L = 600 nm



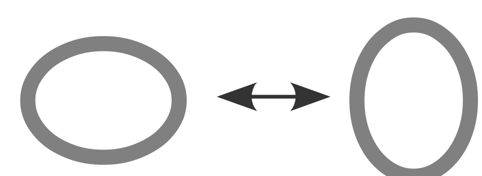
- Stretching modes (confined phonons)



$$\Delta E_{vib} = \hbar v_{ph} q \quad \text{with} \quad q = \frac{n\pi}{L}$$

$v_{ph} = 2.4 \times 10^4$ m/s $\Rightarrow$ Evib = n 0.09 meV for L = 600 nm

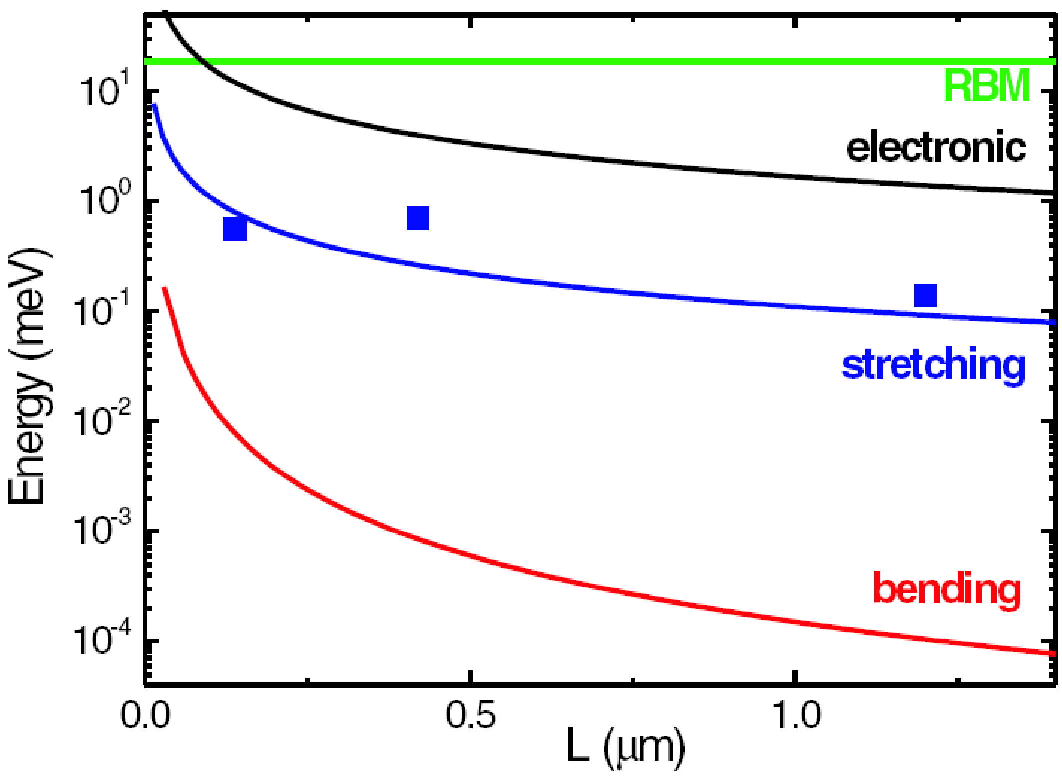
- squash-ball modes (optical)



- twisting modes (weakly coupled to electron tunneling)

Vibrational excited states in a carbon nanotube quantum dot

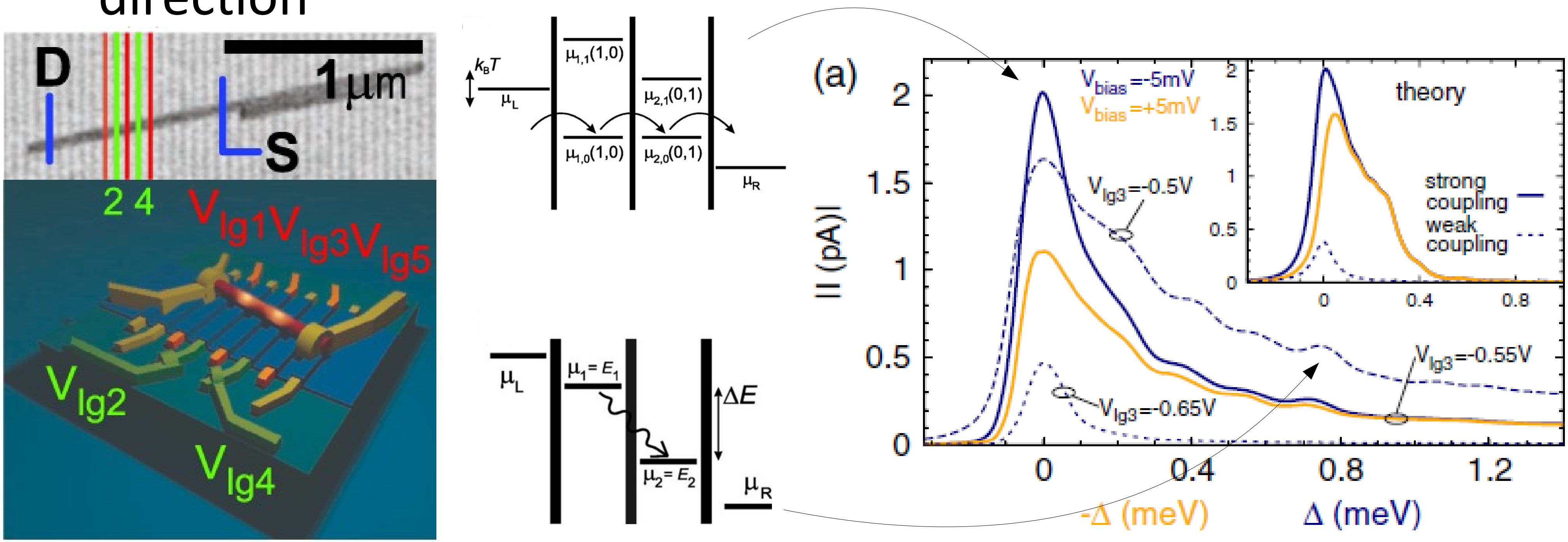
- Energy scale rather corresponds to stretching modes



S. Sapmaz *et al.*, PRL **96**, 026801 (2006)

Signatures of phonon confinement in a nanowire double quantum dot

- Nanowire laying over finger gates: double quantum dot formed by using 5 gates
- Energy scale corresponds to phonons confined in the lateral direction

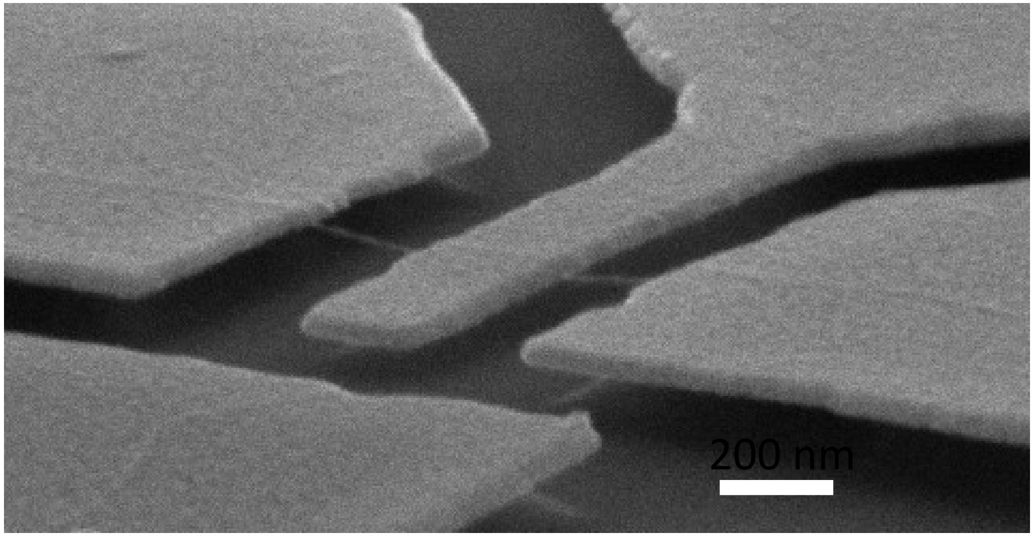


C. Wever et al., Phys. Rev. Lett. 104, 036801 (2010)

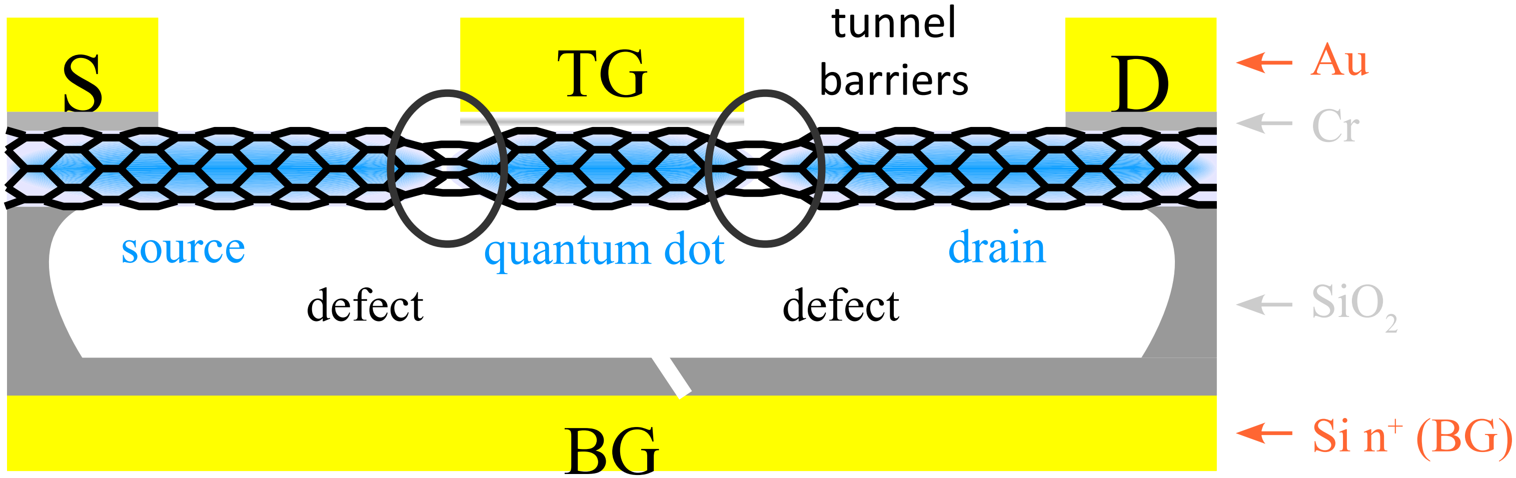
Observation of vibrational excited states

- Observation of vibrational excited states in suspended quantum dots
  - the main argument is the energy scale
- Can we proove further that these excited states are of vibrational origin?

Sample



C. Stampfer *et al.*



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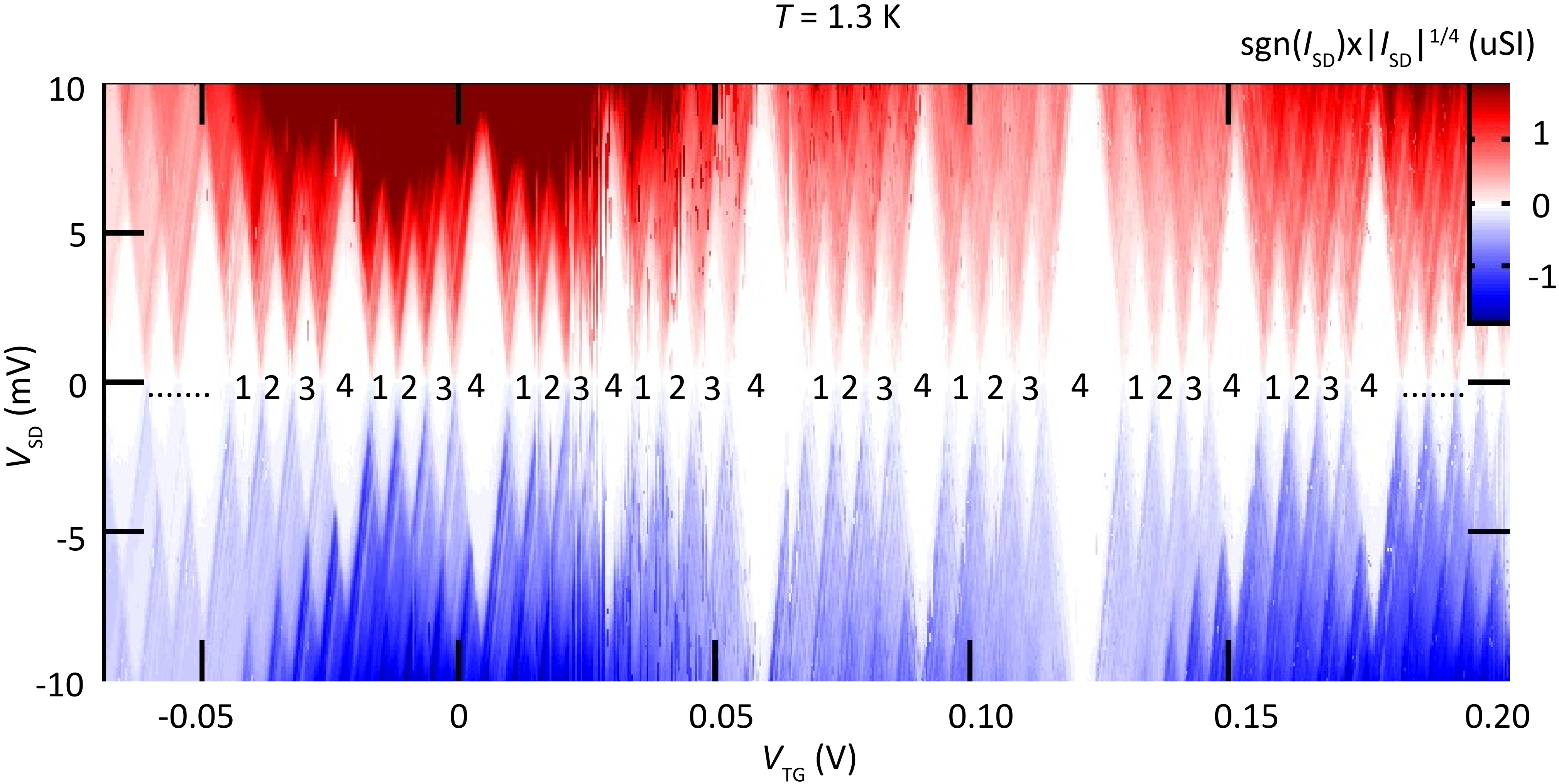
Coulomb diamonds

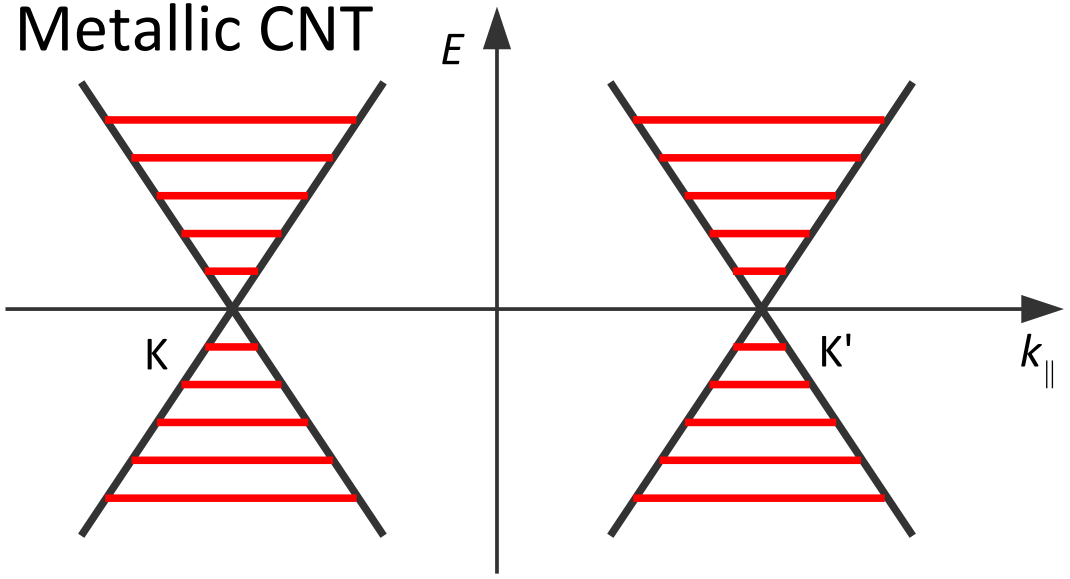


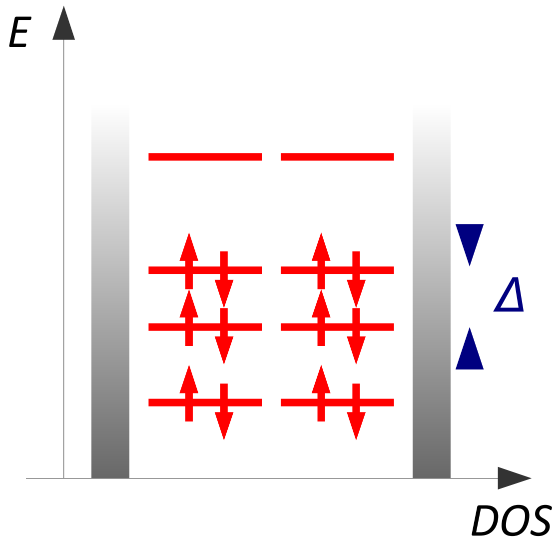
(V_{BG} = -0.7576xV_{TG} + 1.6784 V)

Coulomb diamonds

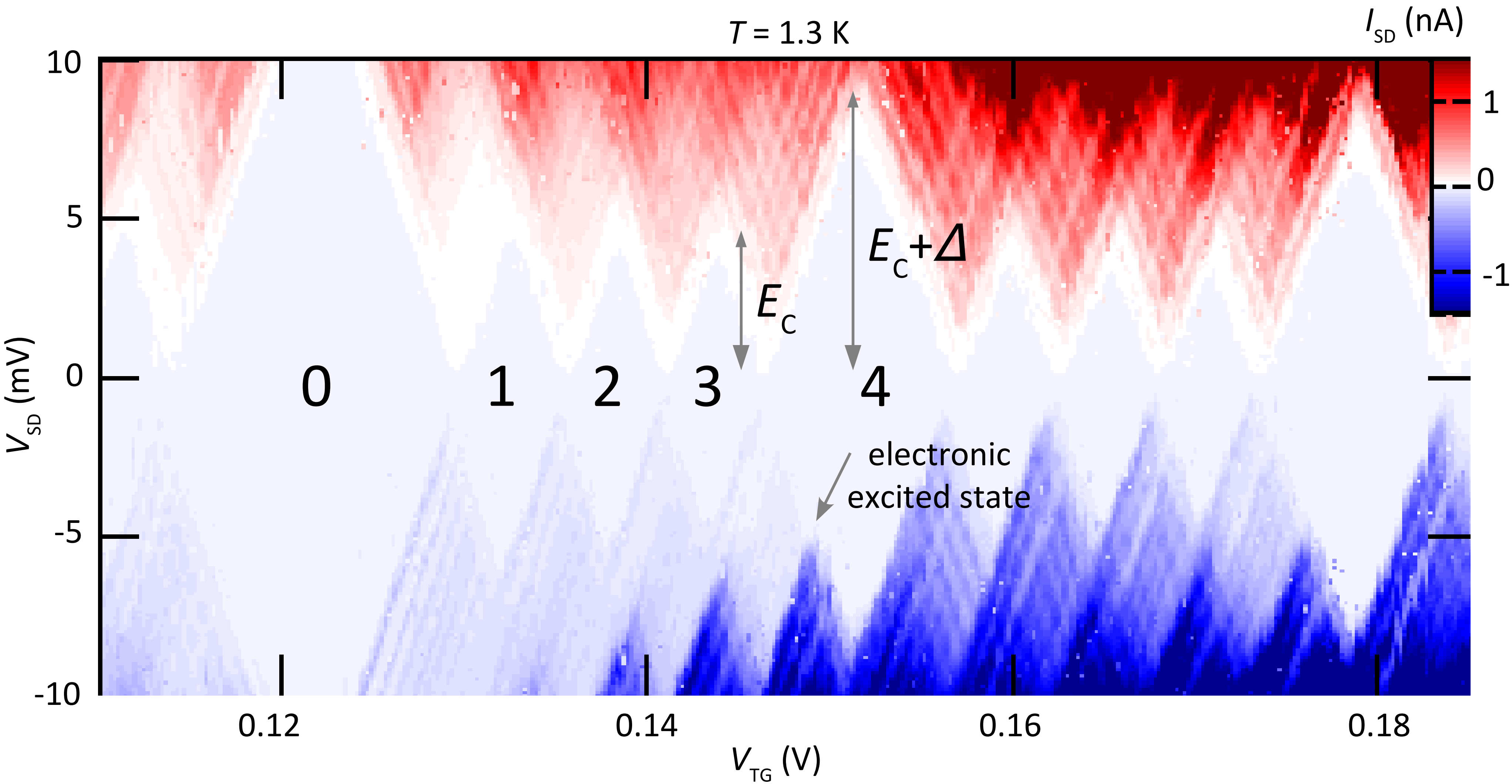
- Quadri-periodic addition energy ⇒ four-fold degeneracy
  - spin degeneracy
  - orbital degeneracy in CNT

Metallic CNT





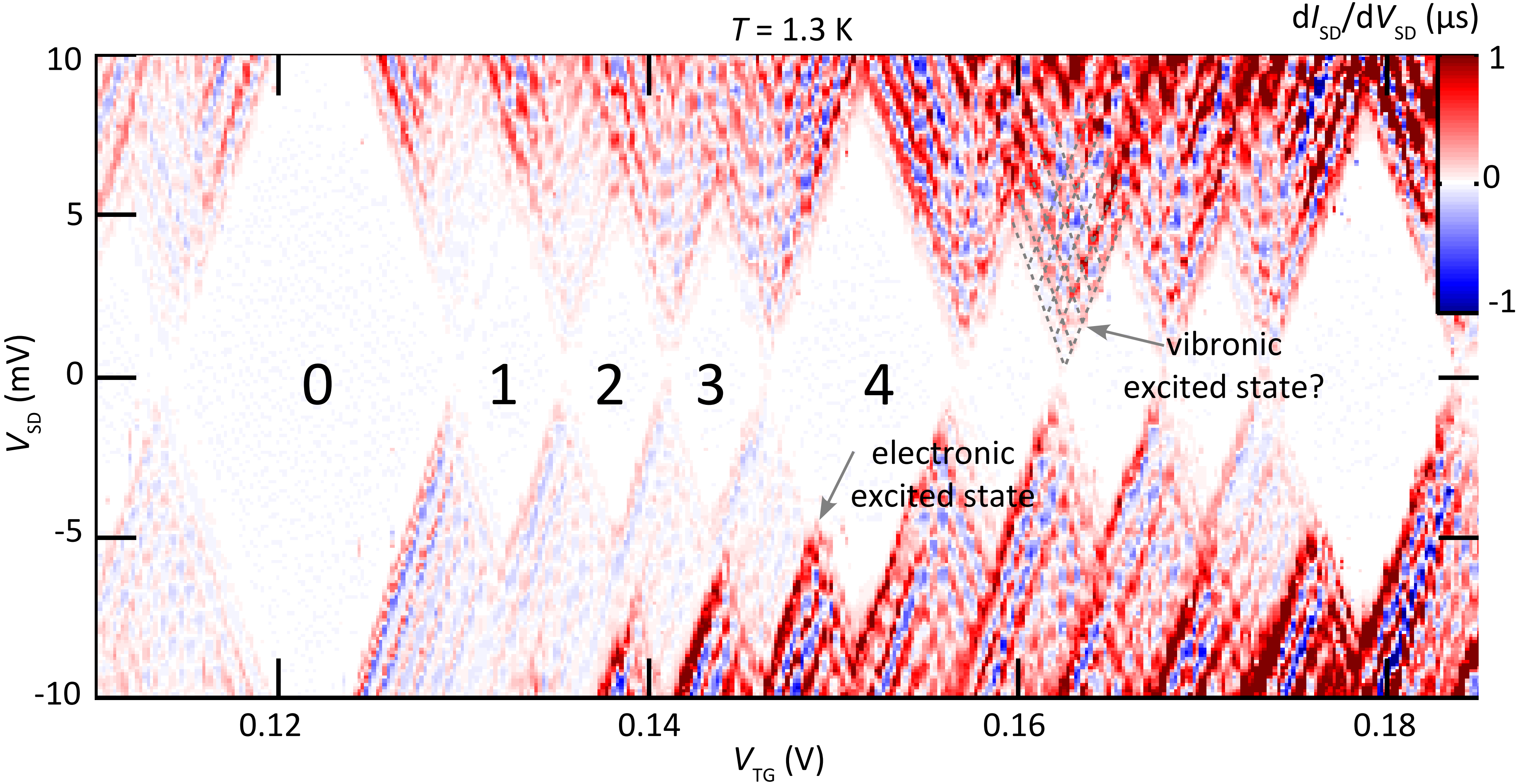
Excited states



Electronic excited states: $\Delta E_{elec} = hv_F/2L_{QD} \approx 7$ meV $\Rightarrow L_{QD} \approx 250$ nm

$v_F = 8.1\text{x}10^5$ m/s – S. G. Lemay *et al.*, Nature **412**, 617 (2001)

Excited states



Vibrational excited states: $\Delta E_{vib} \approx 0.8$ meV $\ll \Delta E_{elec}$

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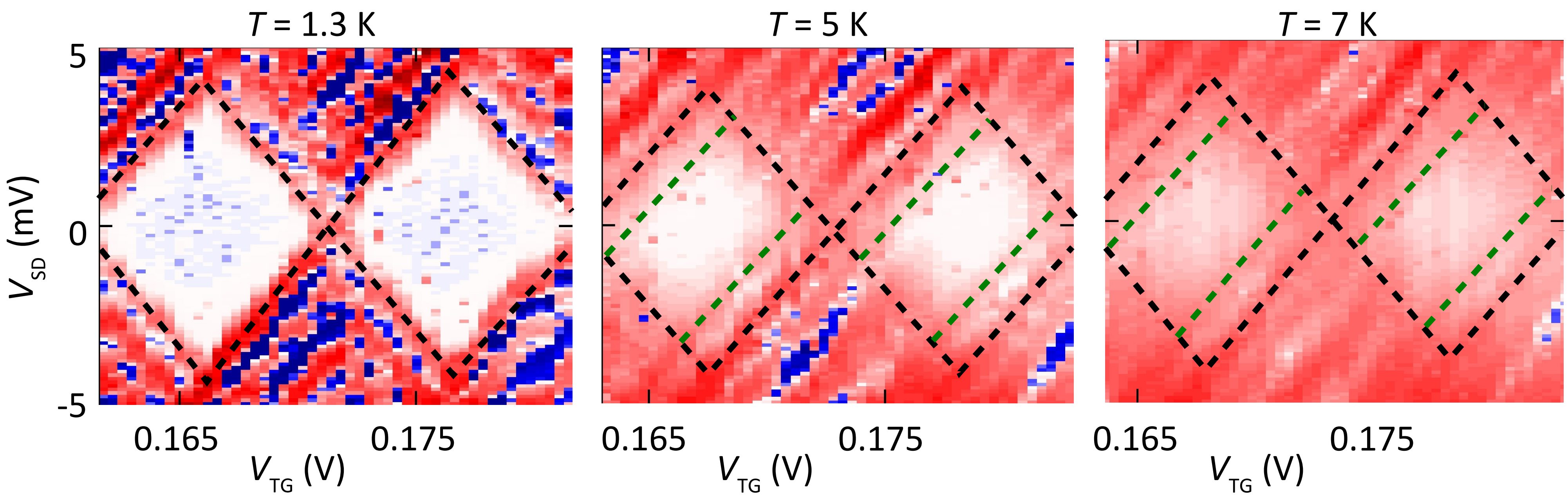
R. Leturcq, C. Stampfer *et al.*, Nature Phys. **5**, 327 (2009)

Evidence of vibronic excited states: temperature dependence

- Vibron-assisted tunneling at higher temperature



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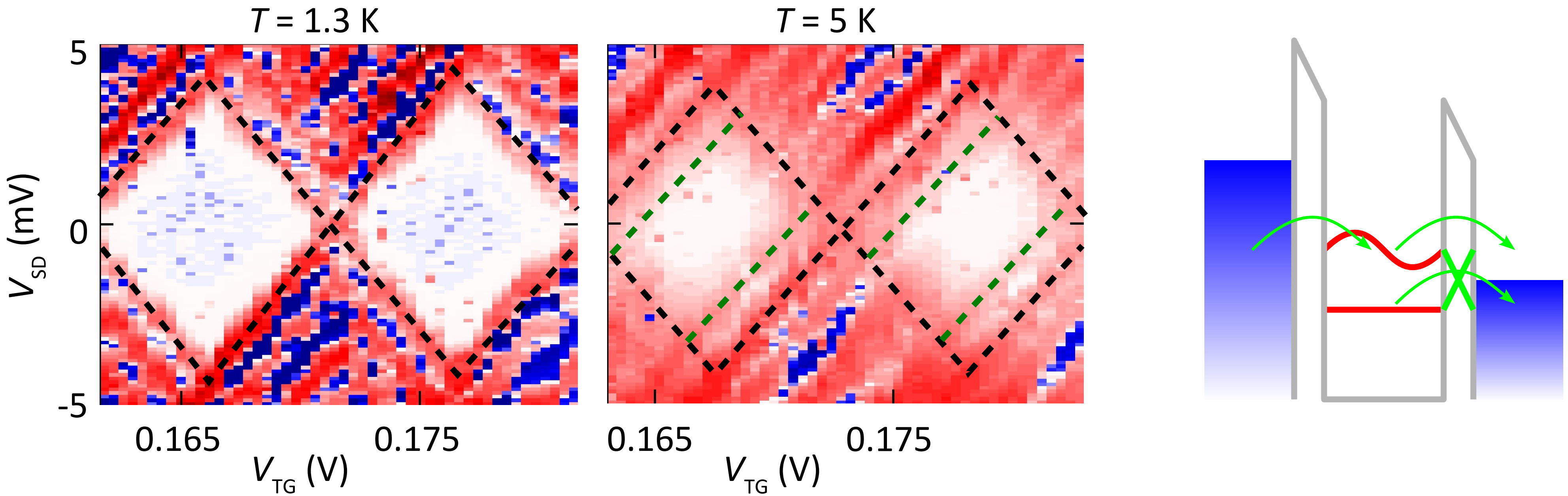

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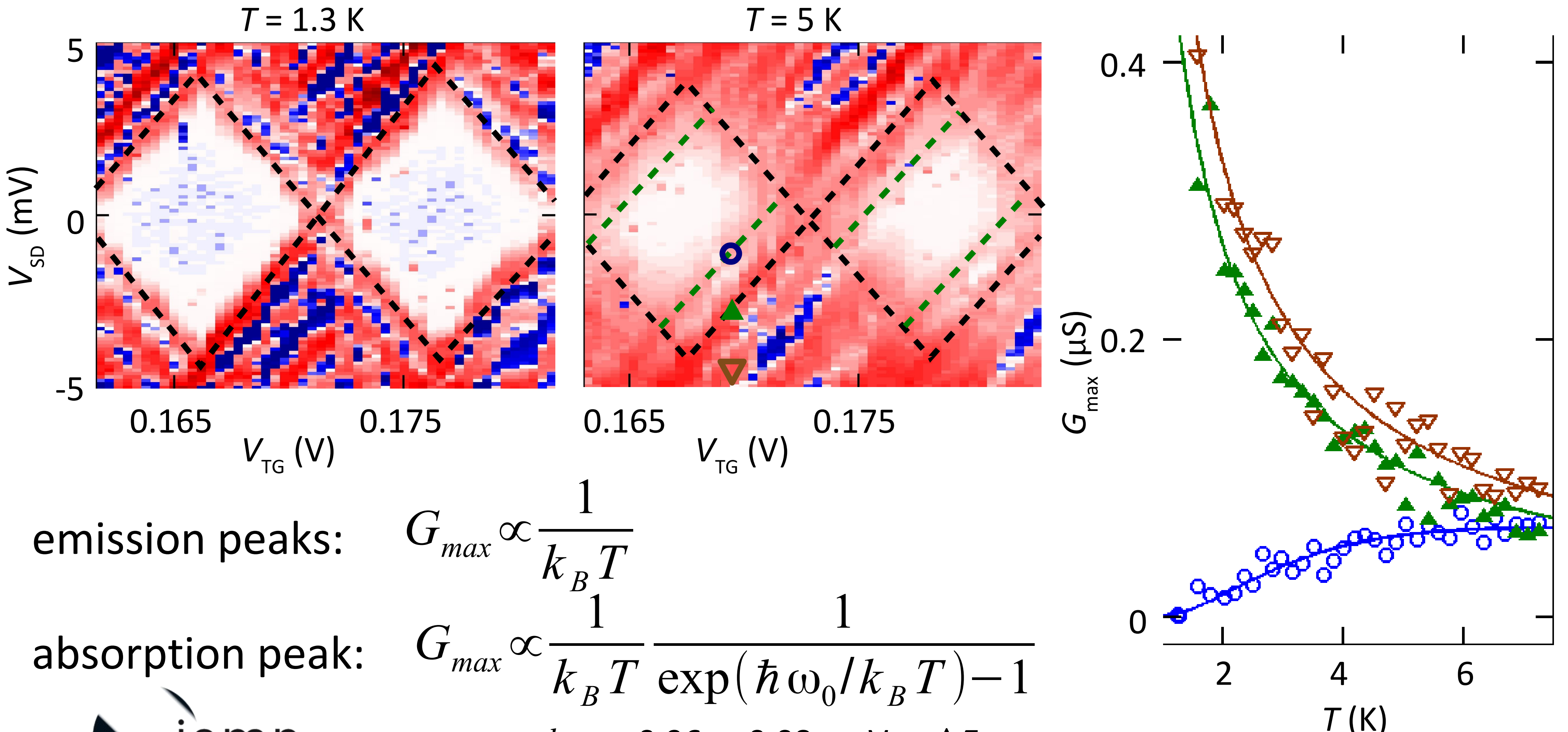

emission peaks: $$G_{max} \propto \frac{1}{k_B T}$$

absorption peak: $$G_{max} \propto \frac{1}{k_B T} \frac{1}{\exp(\hbar\omega_0 / k_B T) - 1}$$

$\hbar\omega_0 = 0.96 \pm 0.08$ meV $\approx \Delta E_{vib}$

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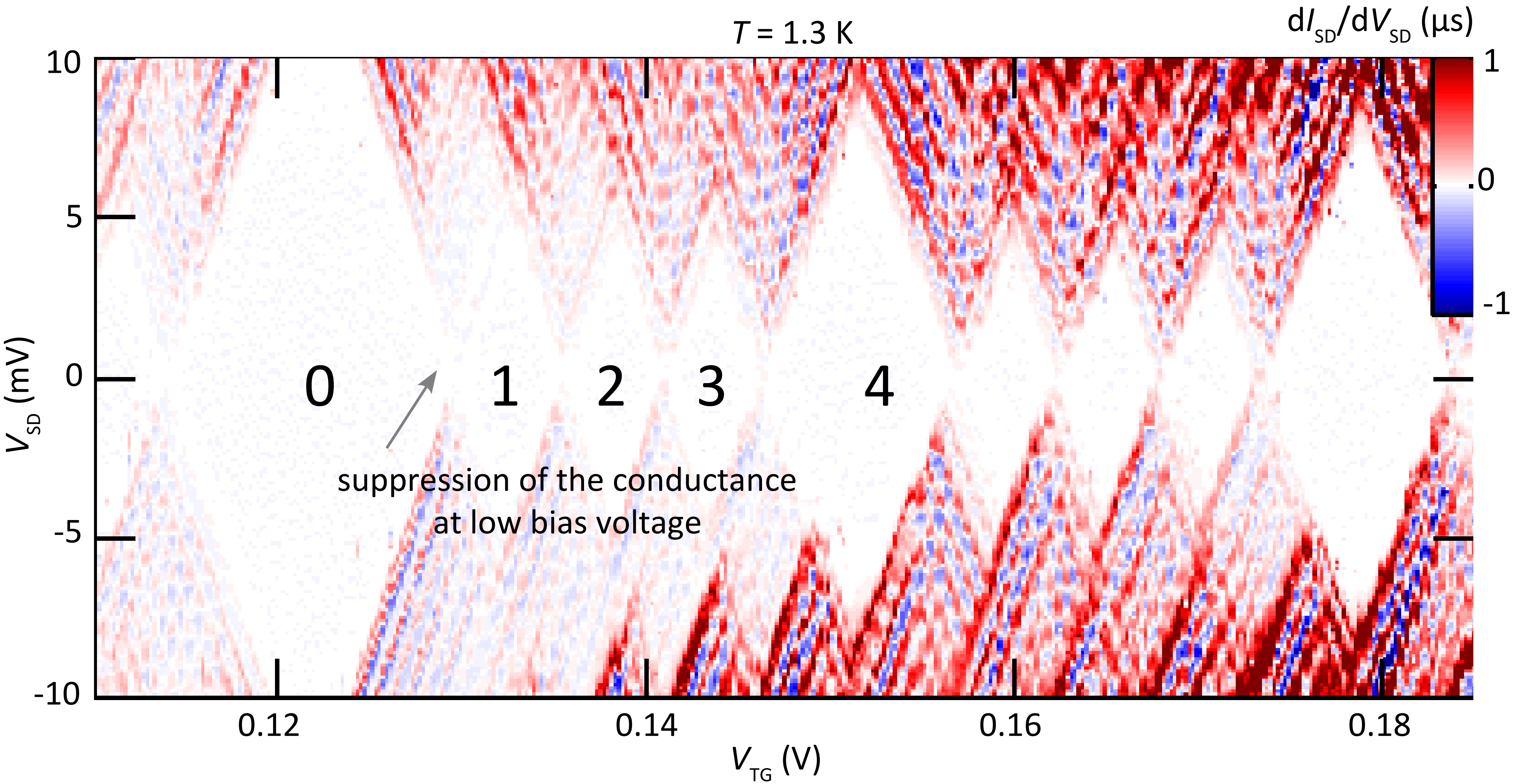
Excited states



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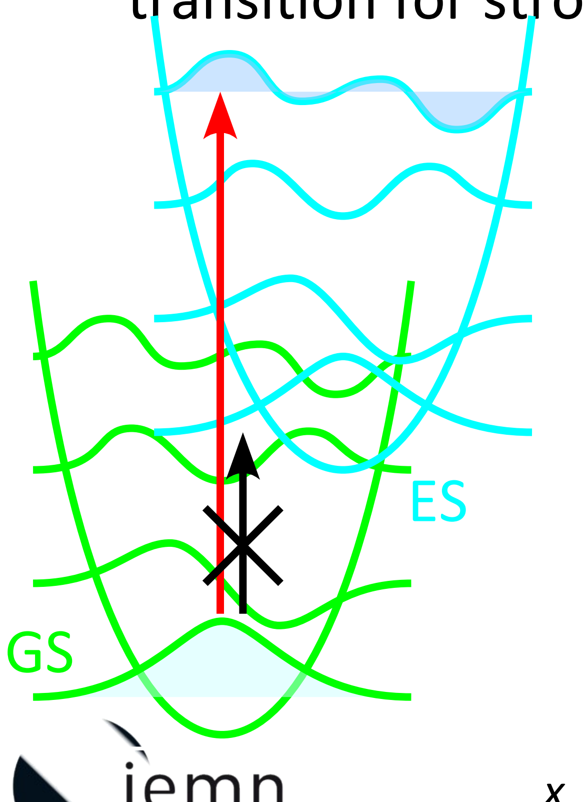
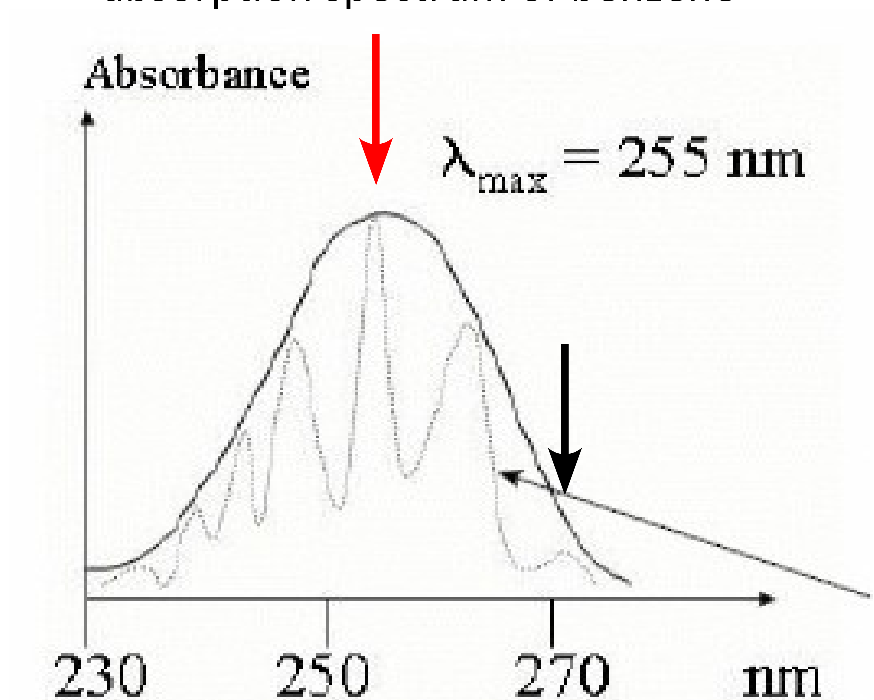
Vibrational spectrum of molecules

- Vibronic transitions: Franck-Condon principle
  J. Franck, Trans. Faraday Soc. 21, 536 (1926); E. Condon, Phys. Rev. 28, 1182 (1928)
  - suppression of the vibrational ground-state to ground-state transition for strong electron-vibron coupling



absorption spectrum of benzene

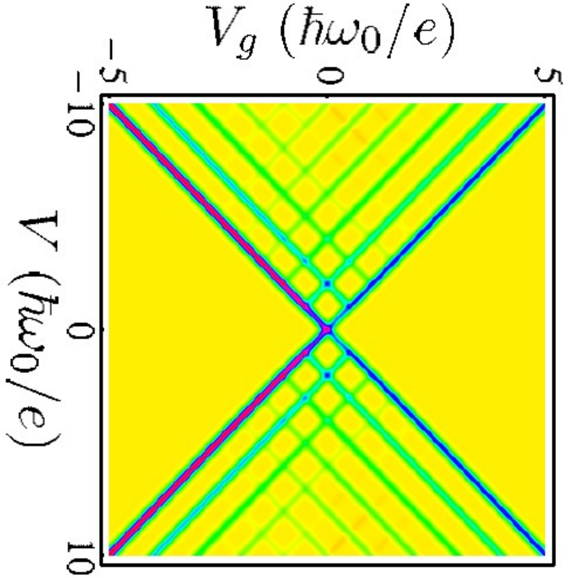


benzene dissolved in cyclohexane

Vibrational spectrum of molecular quantum dots

- Franck-Condon principle ⇒ suppression of the current at zero bias voltage = “Franck-Condon blockade”
  J. Koch & F. von Oppen, Phys. Rev. Lett. 94, 206804 (2005)

weak
e-vibron coupling



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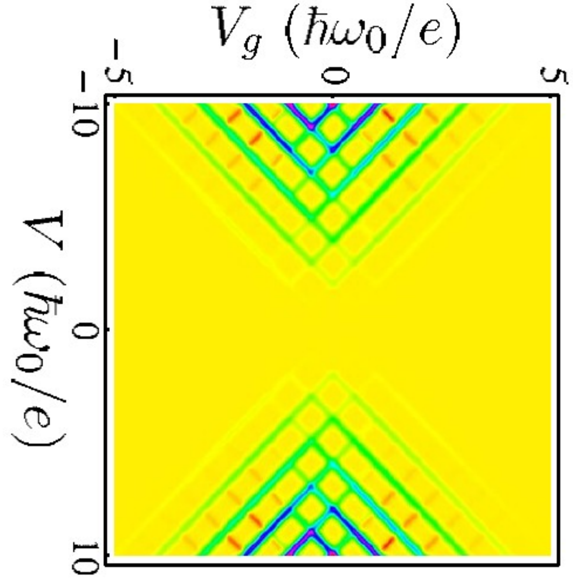
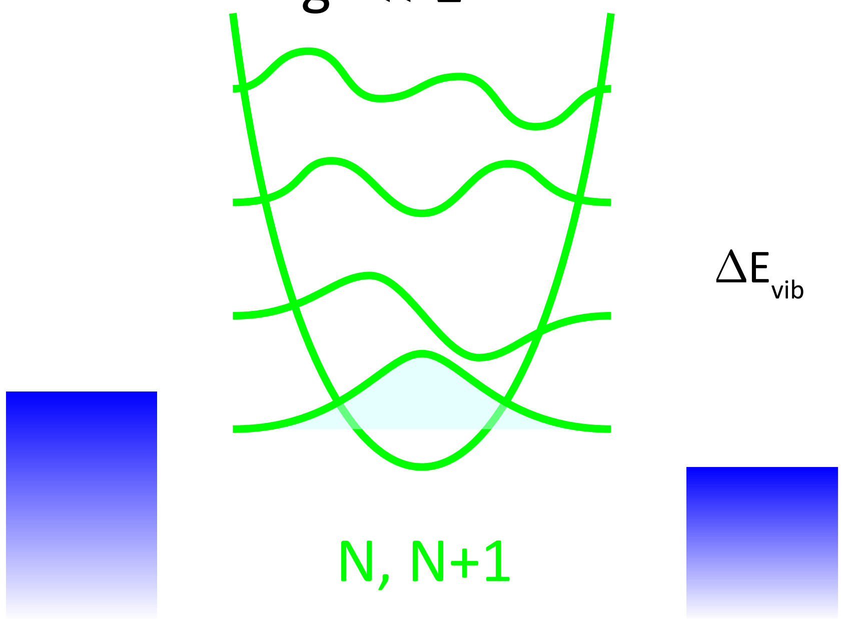


weak electron-vibron coupling

$g \ll 1$



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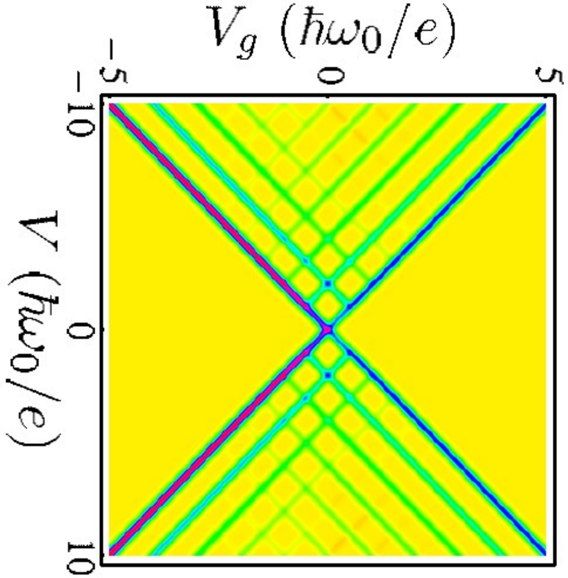

strong
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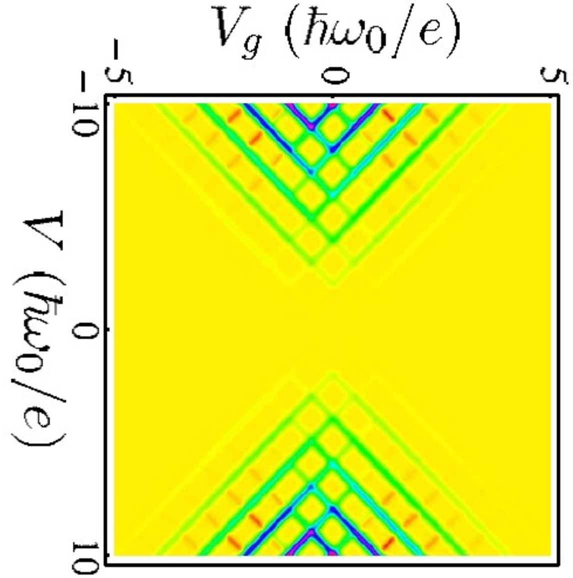
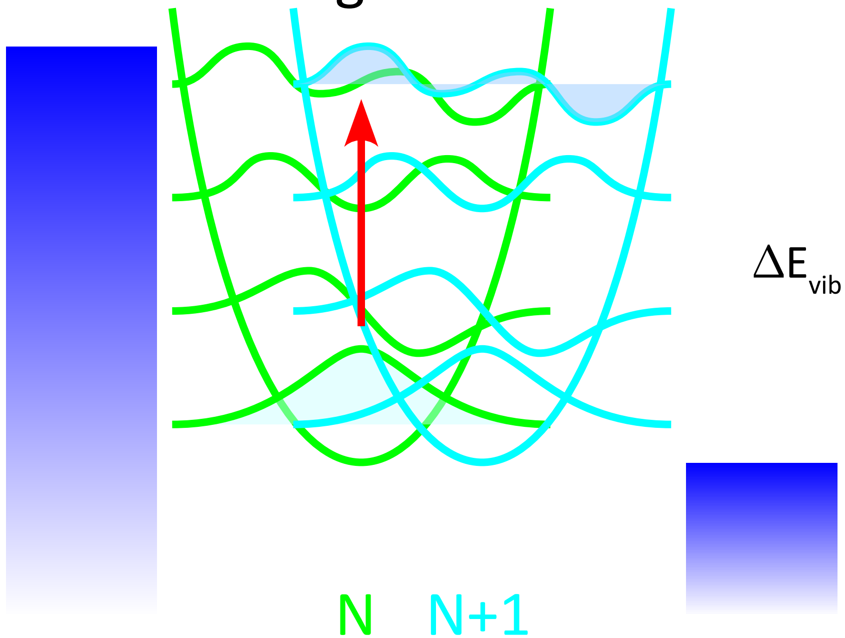


strong electron-vibron coupling

g > 1



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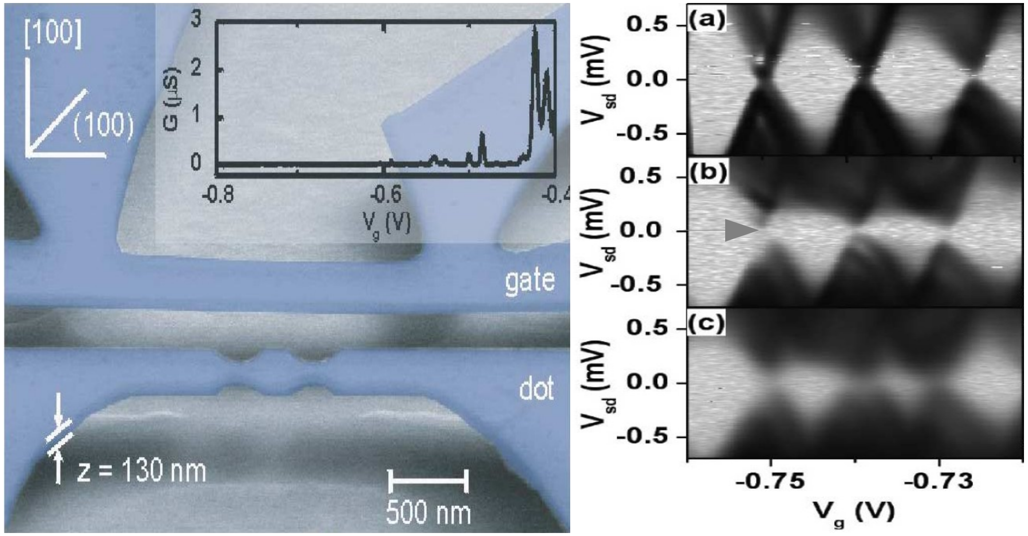

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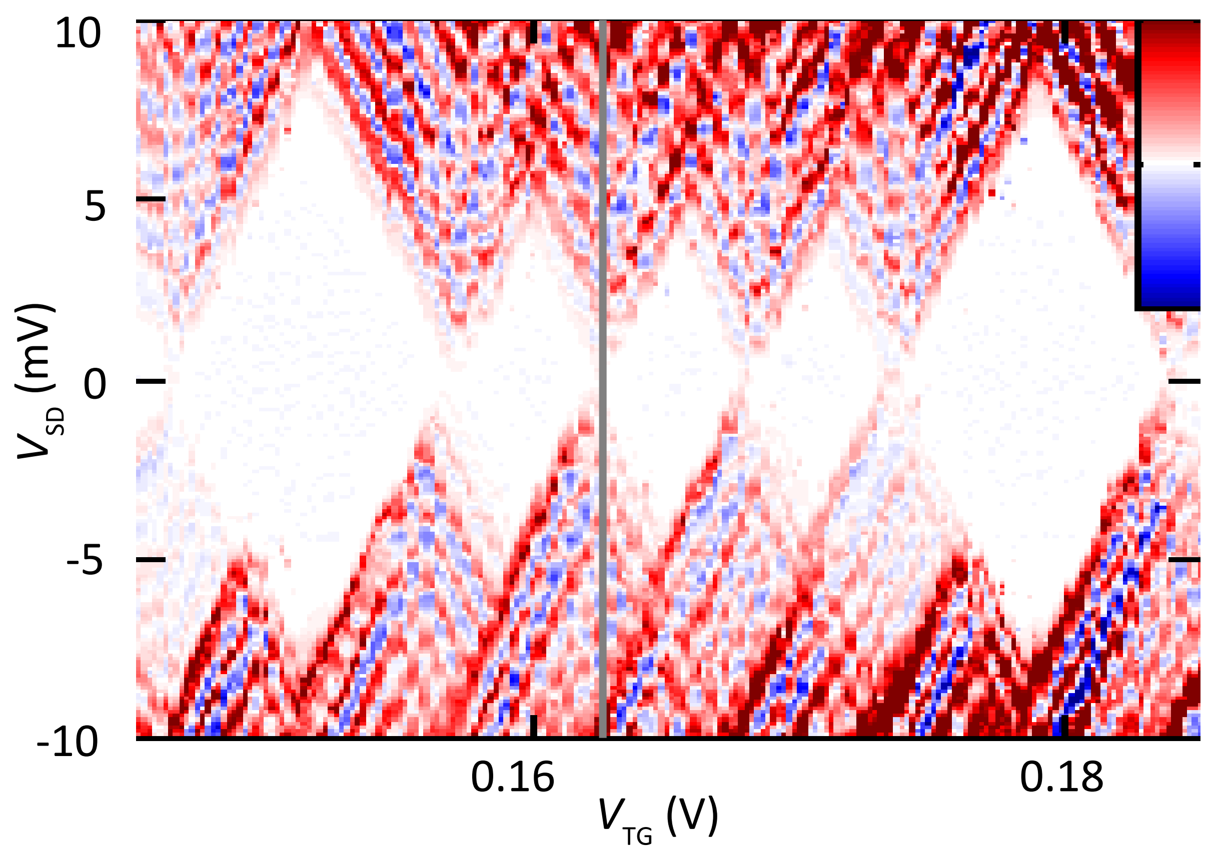
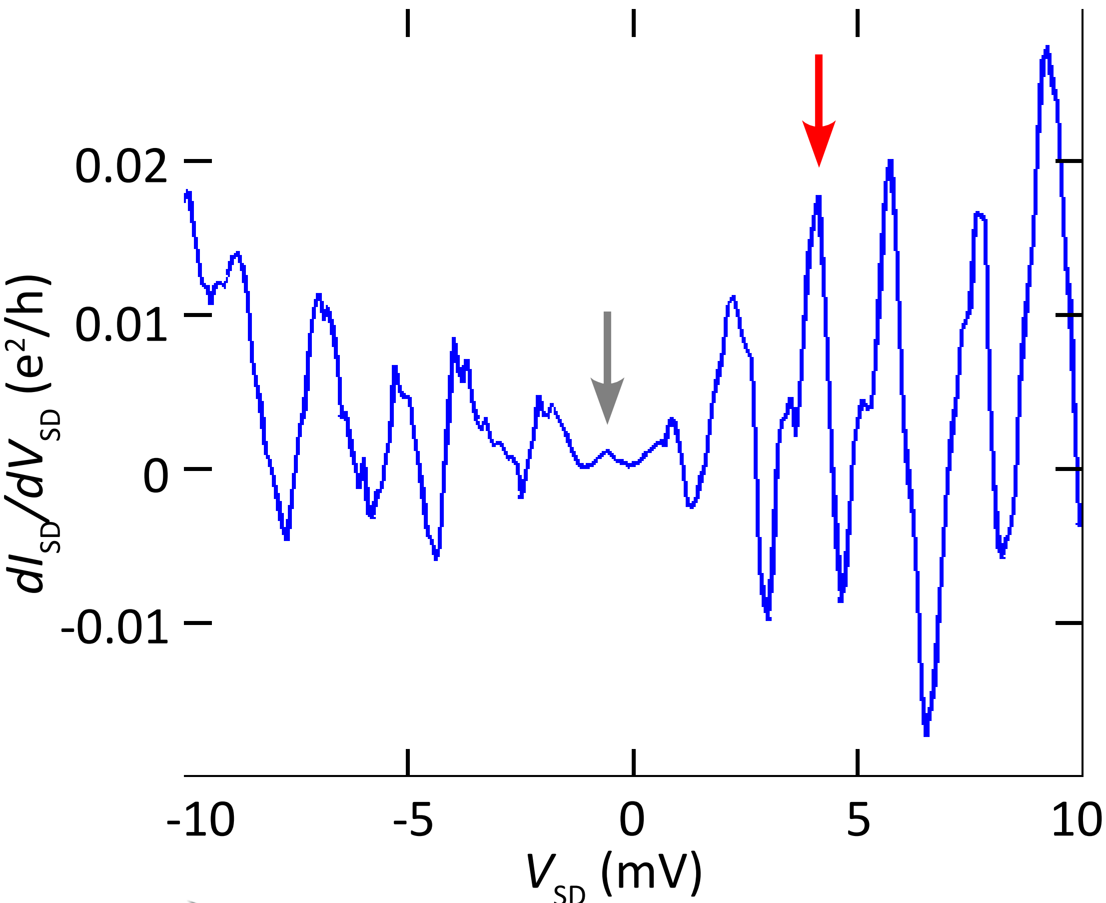


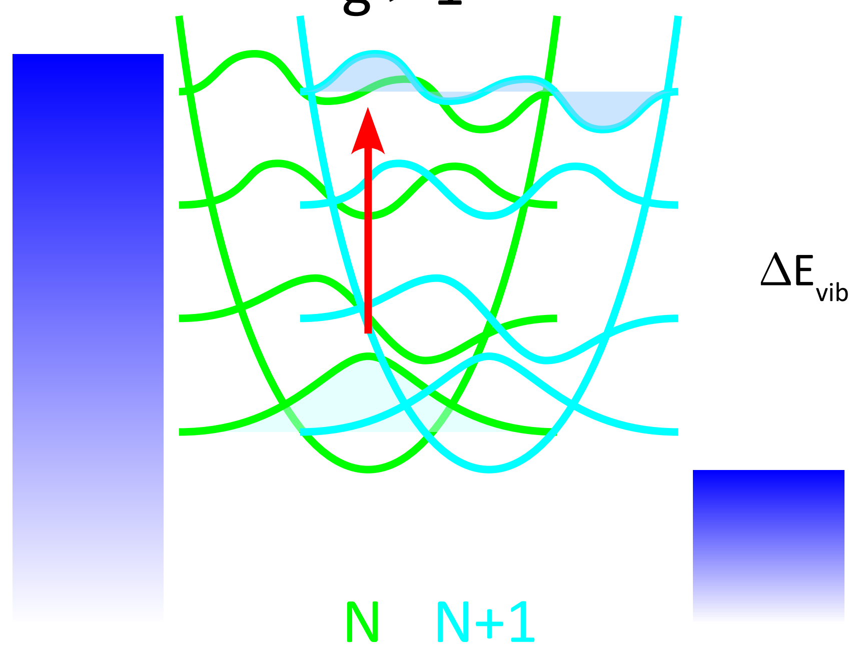
Franck-Condon blockade

- Suppression of the current at zero bias voltage



strong electron-vibron coupling

g > 1



R. Leturcq, C. Stampfer *et al.*, Nature Phys. **5**, 327 (2009)

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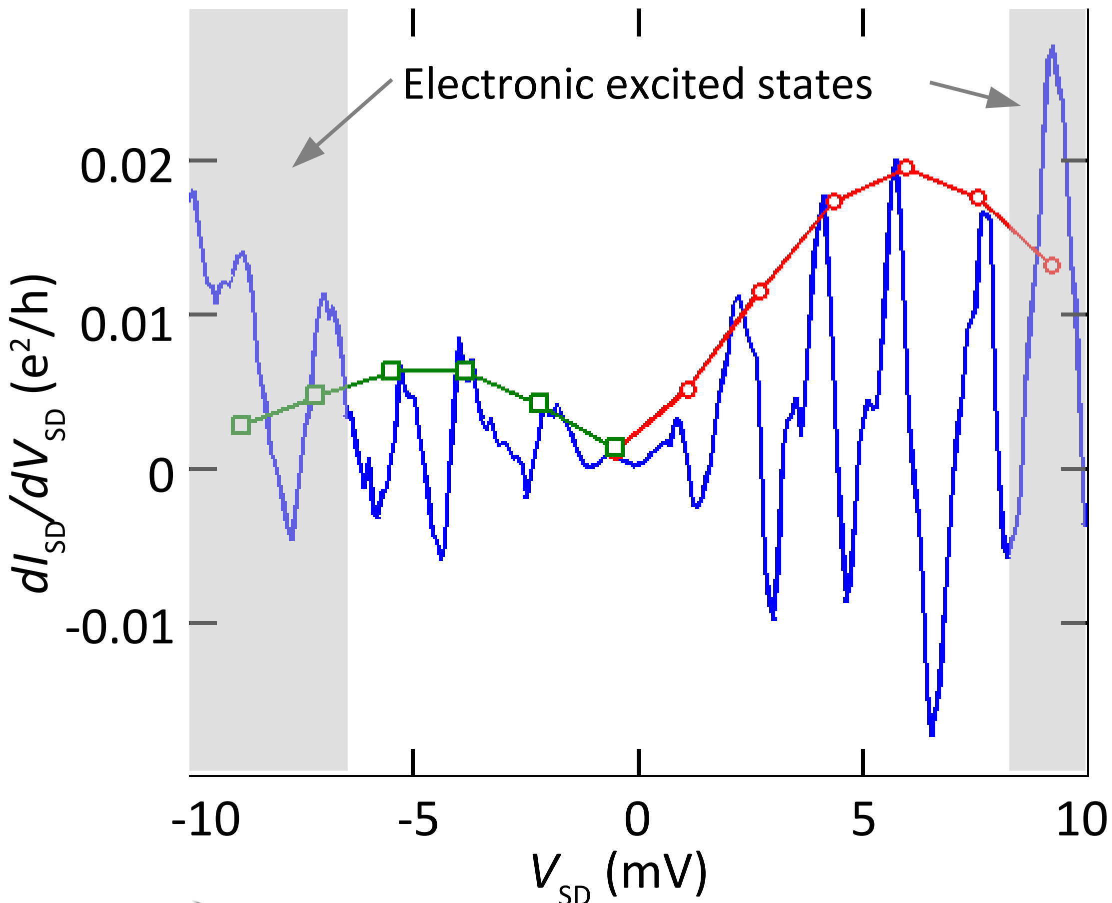
Franck-Condon blockade

- Suppression of the current at zero bias voltage



Franck-Condon factors:

$$\left(\frac{dI_{SD}}{dV_{SD}}\right)_n^{max} \propto \left|M_{0\to n}\right|^2 \propto \frac{e^{-g} g^n}{n!}$$

electron-vibron coupling parameter:

$g = 3 – 5 > 1$

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Summary

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  - Quantum effects on electronic transport: for a sufficiently small size and at low temperature!
  - In these conditions, electronic properties of small nanostructures ressemble those of artificial atomes or molecules
- Part 2: Coupling of electrical and mechanical degrees of freedom
  - Suspended nanotructures show a vibrational spectrum similar to the one of molecules (as far as for Franck-Condon effect)
  - Observation of the electron-phonon coupling at the single particle level
  - Further reading: control of single phonons in a mechanical resonator [O'Connell *et al.*, Nature **464**, 697 (2010)]