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Towards microwave optomechanics using a superconducting carbon nanotube weak link

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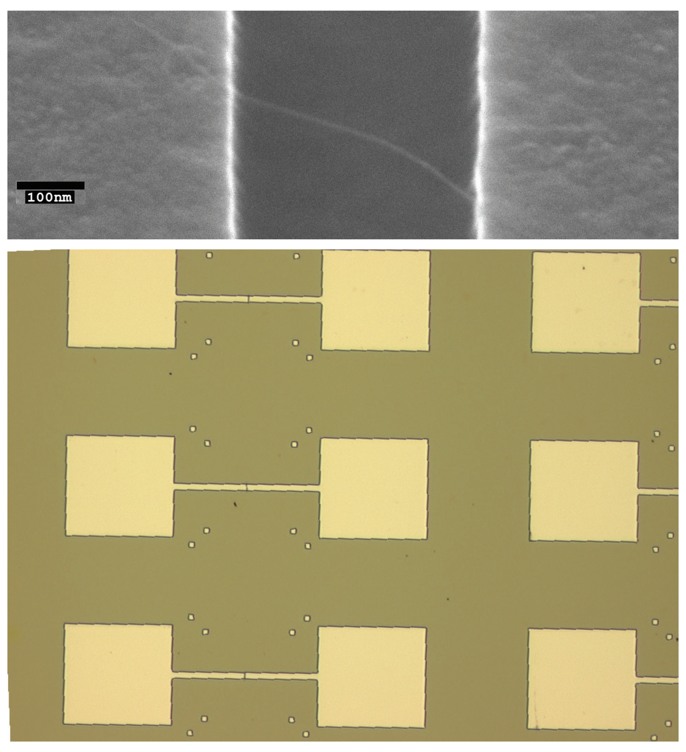
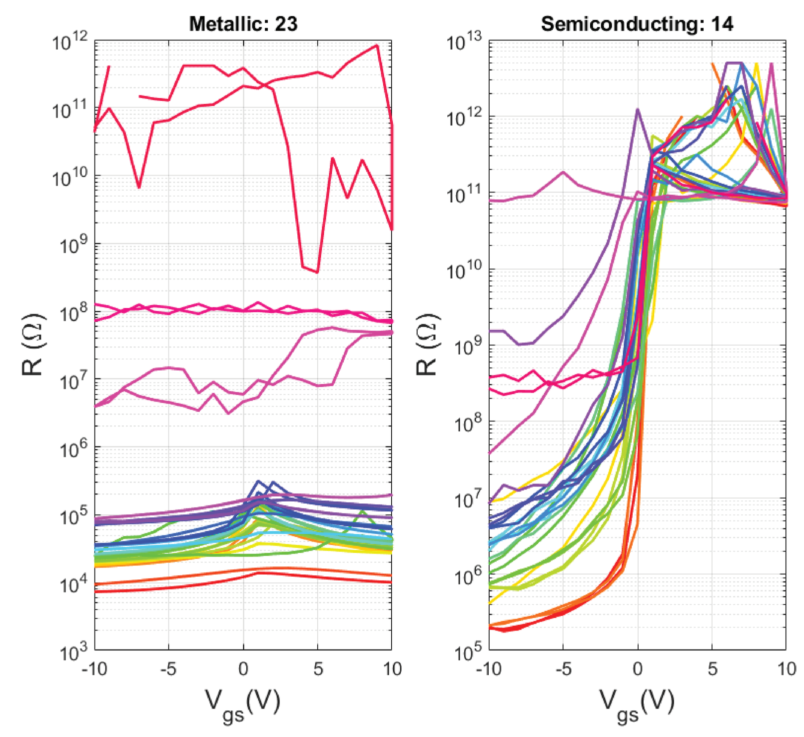
Abstract

Utilizing the ultra-high sensitivity of a superconducting single-walled carbon nanotube (SWCNT) sensor to probe the quantum ground state is a promising experimental approach for investigations of macroscopic quantum phenomena. We approach the challenge with suspended, 300 nm long SWCNT contacted on MoRe leads. MoRe is used because it can withstand temperatures above 900 °C. Such temperatures are used in our annealing process as well as in CNT CVD growth processes. Good transparency of the superconductor-nanotube contacts allows observation of proximity induced supercurrents of up to 50 nA, tuneable by gate induced charge. Additionally, we have developed a method to pick-up and place individual suspended SWCNT selectively on metal-electrodes. Using such weak links in an optomechanical microwave setting, coupling energies on the order of 2 MHz can be reached between the mechanical resonator and the electrical cavity.

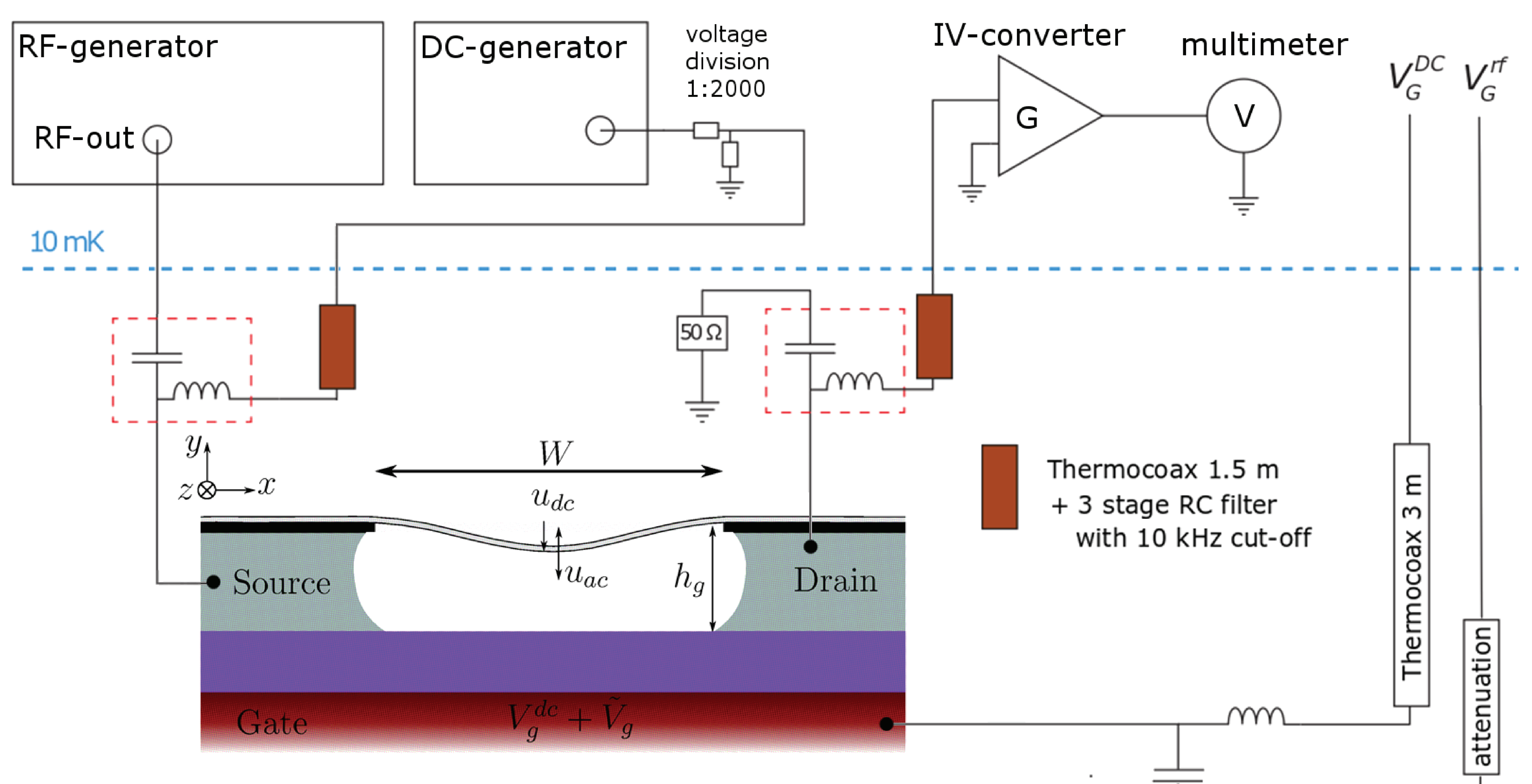
Measuring supercurrent in CNT

- We fabricated source/drain pairs of 200 nm MoRe [1] and a separation of 300 nm and deposited aerosol-synthesised [2] carbon nanotubes onto a chip with multiple pairs.

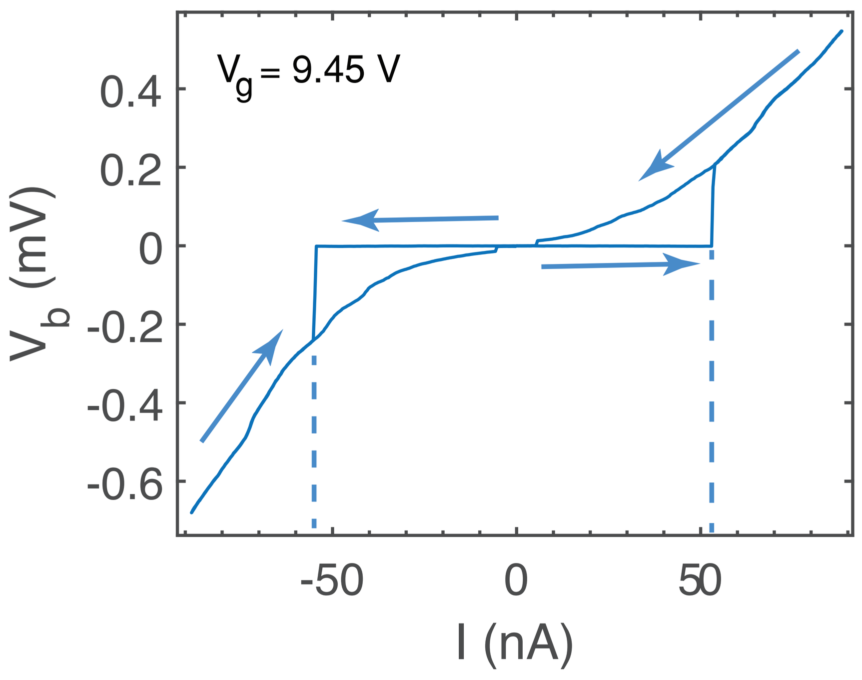


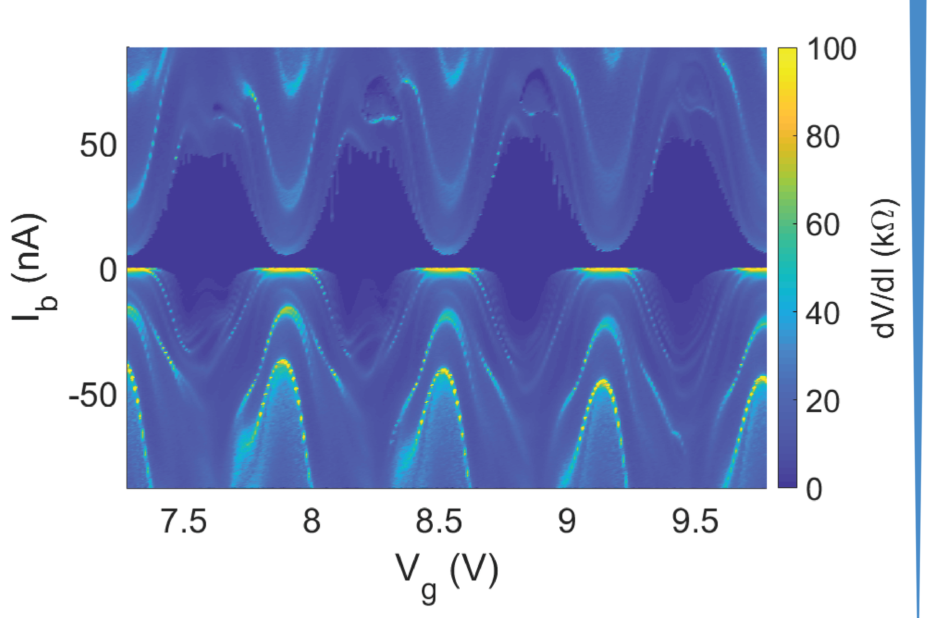


- Promising tubes are selected and cooled down to 10 mK.

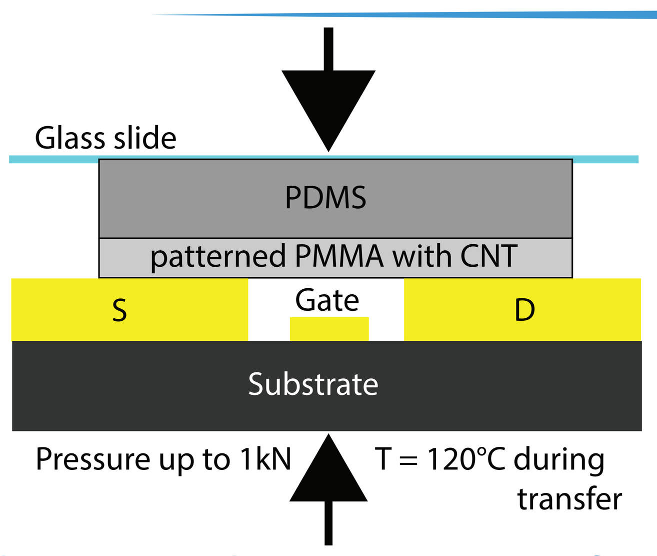


- We can measure a supercurrent of up to 52 nA with a responsivity of $\partial I_C/\partial V_g = 290\,\mathrm{nA\,V^{-1}}$.

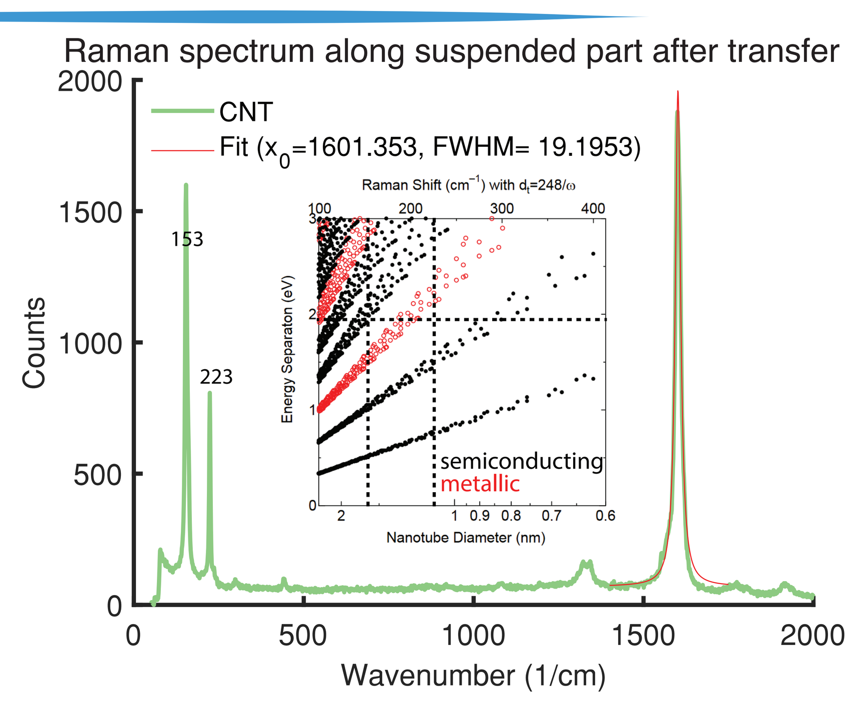




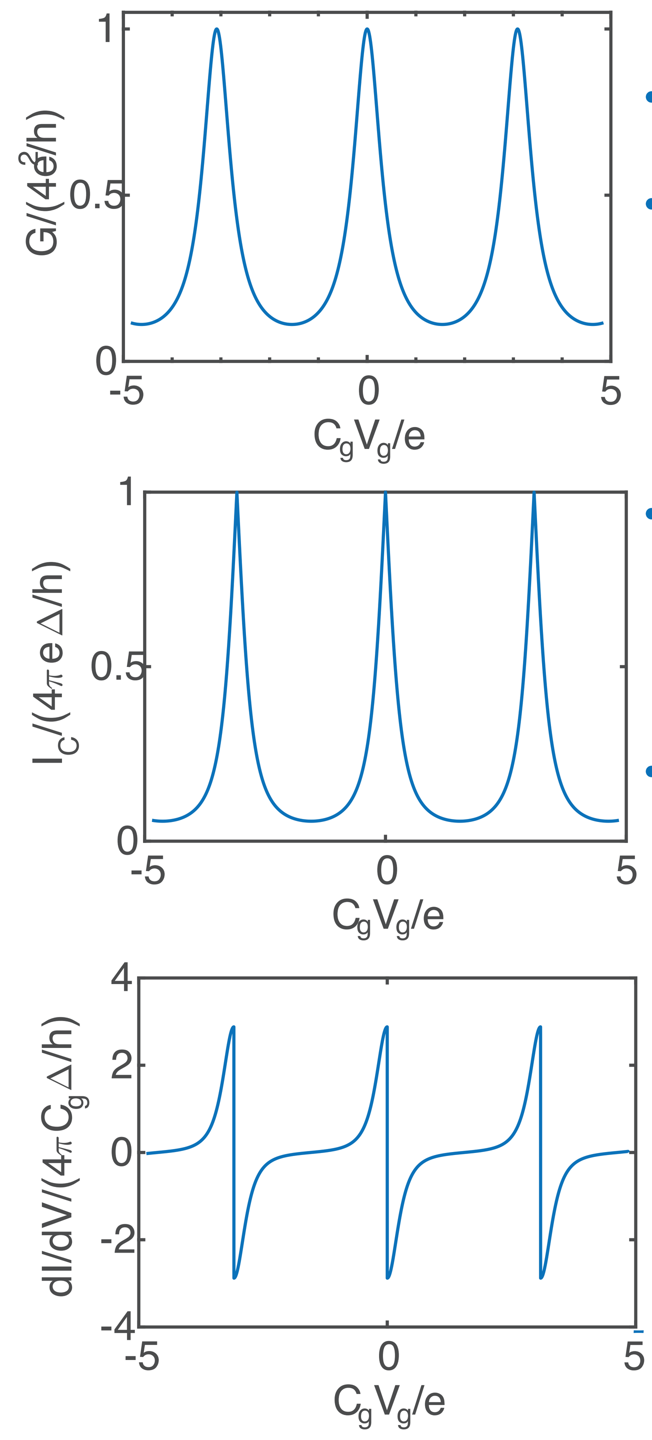
Carbon nanotube transfer



- CVD grown CNTs are picked up from a separate chip at 70 °C. The PMMA is patterned with holes of 2 µm × 10 µm.



Limits of CNT supercurrent



- CNT coupled to two leads with equidistant energy levels and and four time degenerate (two valleys and two spins)
- The escape rates to both sides are then given by $\tau_R > 0.5$ and $\tau_L > 0.5$ (no Coulomb blockade) and the CNT has 4 channel with a transparency

$$\tau = \frac{\tau_R\tau_L}{1+(1-\tau_L)(1-\tau_r)-2\sqrt{(1-\tau_L)(1-\tau_R)}\cos\frac{\pi n_g}{2}}$$

- We can express the conductivity and and the critical current as followed

$$G = \frac{2e^2}{\pi\hbar}\tau \quad \text{and} \quad I_C = \frac{2e\Delta}{\hbar}\frac{\tau}{1+\sqrt{1-\tau}}.$$

- We can estimate the maximum critical current I_C and responsivity $\partial I_C/\partial V_g$ for our geometry

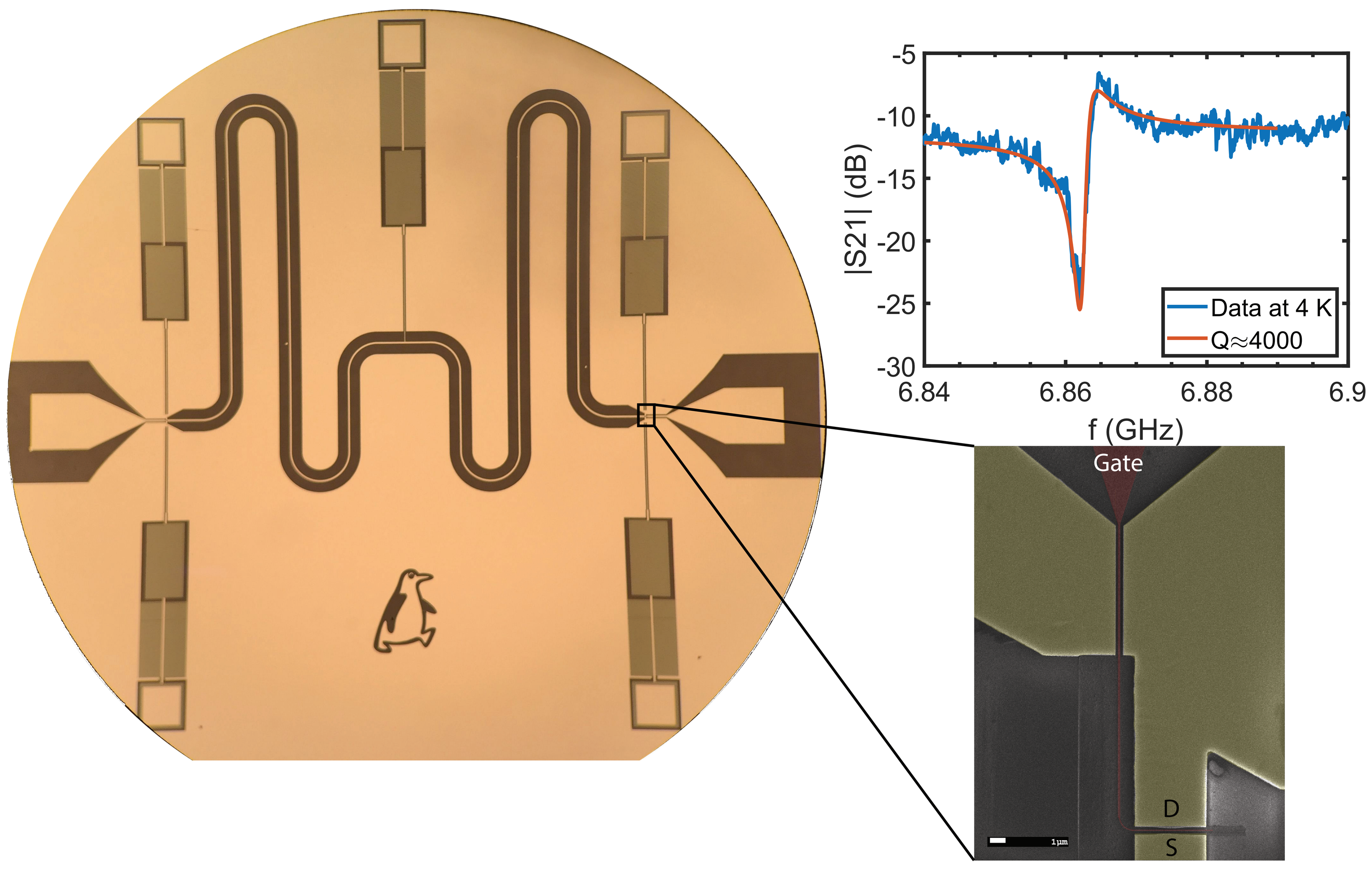
$$\left.\frac{\partial I_C}{\partial V_g}\right|_{\max} \approx \frac{4C_g\Delta}{\hbar} = \frac{8\pi L\Delta\epsilon_0}{\hbar L \ln(R_{\max}/r_0)} \approx 1\times 10^{-5}\frac{1}{\Omega}$$

and

$$I_C^{\max} = \frac{2e\Delta}{\hbar} \approx 300\,\mathrm{nA},$$

with $\Delta = 600\,\mu\mathrm{eV}$ ($T_C = 4$ K), the length of the CNT $L = 300$ nm, $R_{\max} = 200$ nm the distance between gate and nanotube and $r_0 = 1.5$ nm the nanotube radius.

Coupling the CNT to a Cavity



- The cavity readout frequency is around $f_0 = 7$ GHz and a realistic operation point of $I_C = 50$ nA corresponds to a Josephson energy of $E_J/2\pi\hbar = 24$ GHz and a charging energy $E_C/2\pi\hbar = 2$ GHz
- The coupling between the Qubit and phonon corresponding to the CNT vibration is

$$\frac{g}{2\pi} \approx \frac{\partial\omega_0}{\partial L}\delta L_{J,zpm} = \frac{\omega_0}{2}\frac{L/L_j}{L+L_j}\delta L_{J,zpm} \approx 2\,\mathrm{MHz}$$

Summary and Future outlook

- We analyzed the working principle and limiting factors of a suspended CNT resonator on MoRe source/drain pairs.
- The contact resistance of the metal-CNT interface can be decreased by annealing at T= 900 °C and critical currents of 50 nA are measured.
- We characterize CNTs by Raman spectroscopy before transferring these onto pre-patterned electrodes on a device chip.
- A Cavity-CNT single photon-phononcoupling rate of $g_0 \approx 2$ MHz is predicted.
- The combination of suspended CNT and readout cavity introduces new challenges, but also opportunities.

References

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