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Feasibility study on superconducting carbon nanotubes coupled to microwave cavities

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Towards microwave optomechanics using a superconducting carbon nanotube weak link

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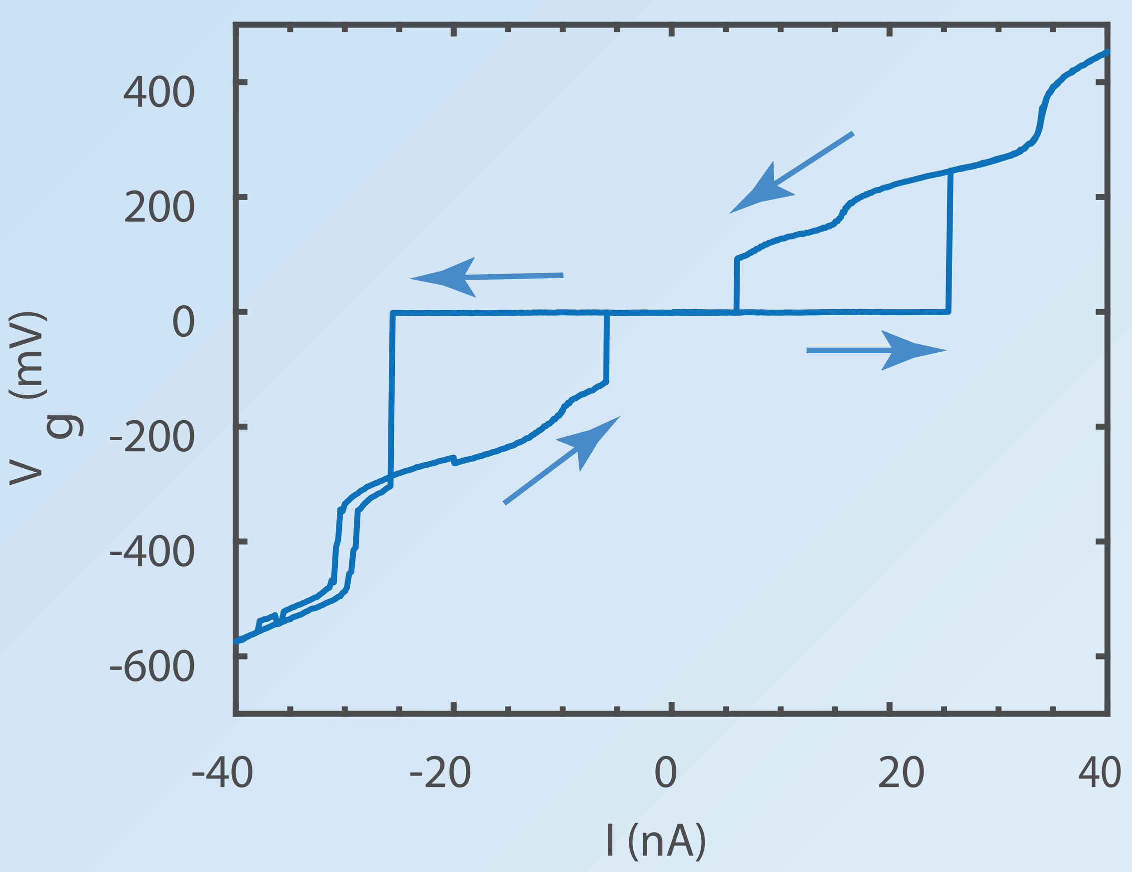
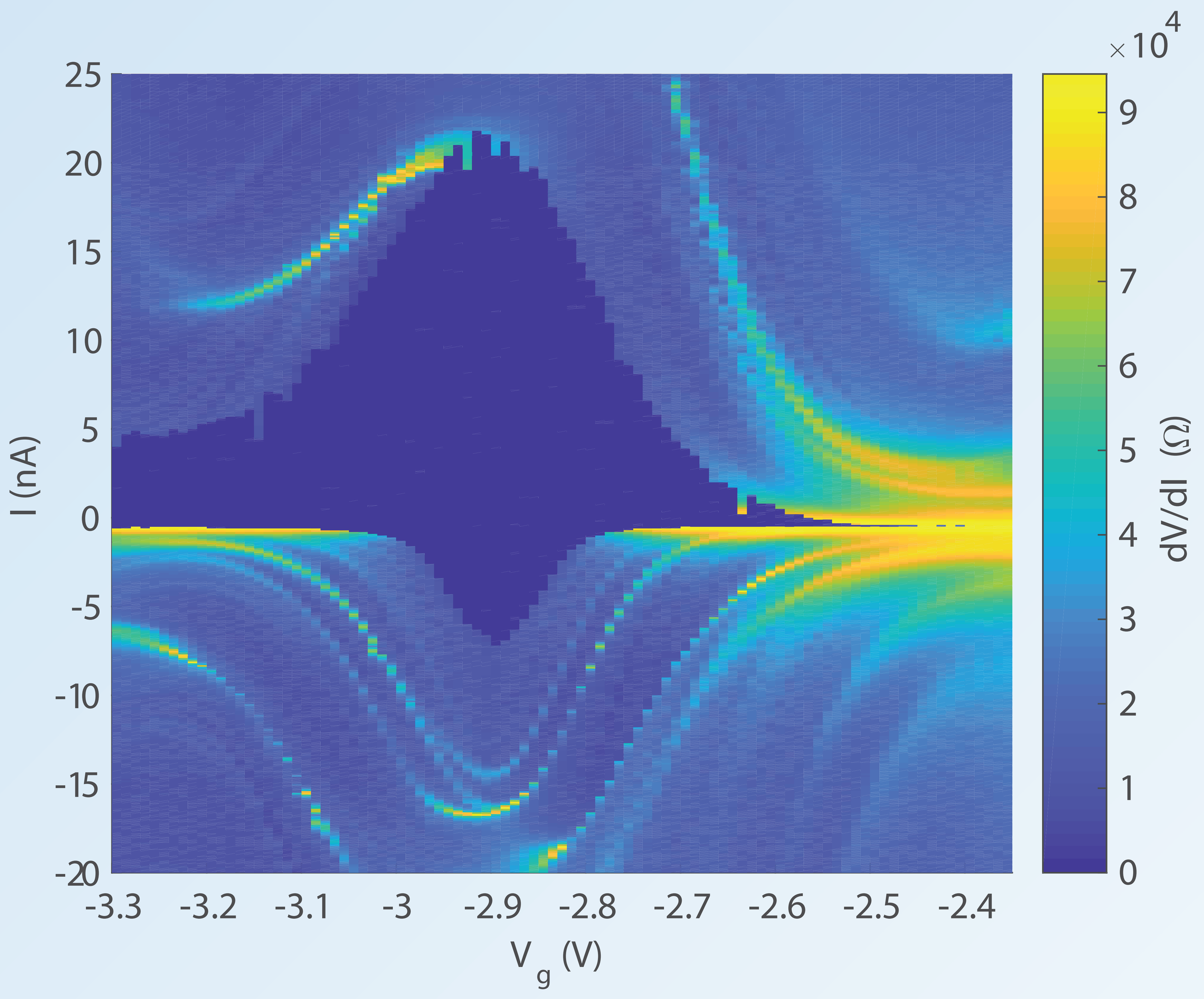
Abstract

Utilizing the ultra-high sensitivity of a superconducting carbon nanotube (CNT) sensor to probe the quantum ground state is a promising experimental approach for investigations of macroscopic quantum phenomena. However, reproducible and reliable fabrication of such devices is still to be shown due to the demands on high temperature stable materials that the CNT growth requires and the crucial role the contact resistance plays for inducing superconductivity into the CNT. We approach the challenge using molybdenum rhenium (MoRe) microwave cavity, which withstands high temperatures. As an alternative for pure MoRe, we have also used a thin coverage of palladium to improve contact resistance to the CNT. We have been able to reach 22 nA critical currents in 250 nm long single walled CNTs. These devices displayed good gate modulation characteristics with 85 nA V^{-1}. Using such weak links in an optomechanical microwave setting, coupling energies on the order of 100 kHz can be reached between the mechanical resonator and the electrical cavity.

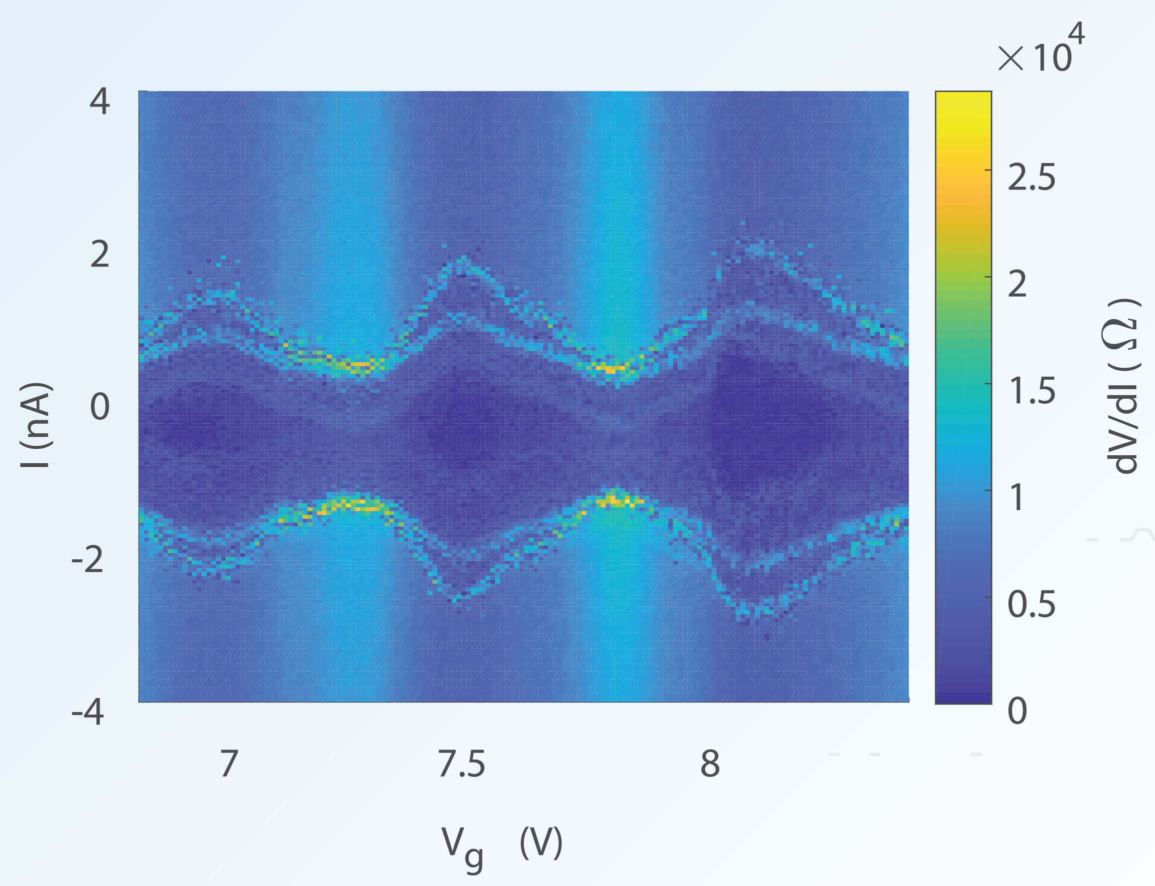
Measuring supercurrent in CNT

- We fabricated source/drain pairs of 50 nm MoRe [1] and a separation of 250 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 22 nA with a responsivity of $\partial I_C/\partial V_g = 85\,\mathrm{nA\,V^{-1}}$

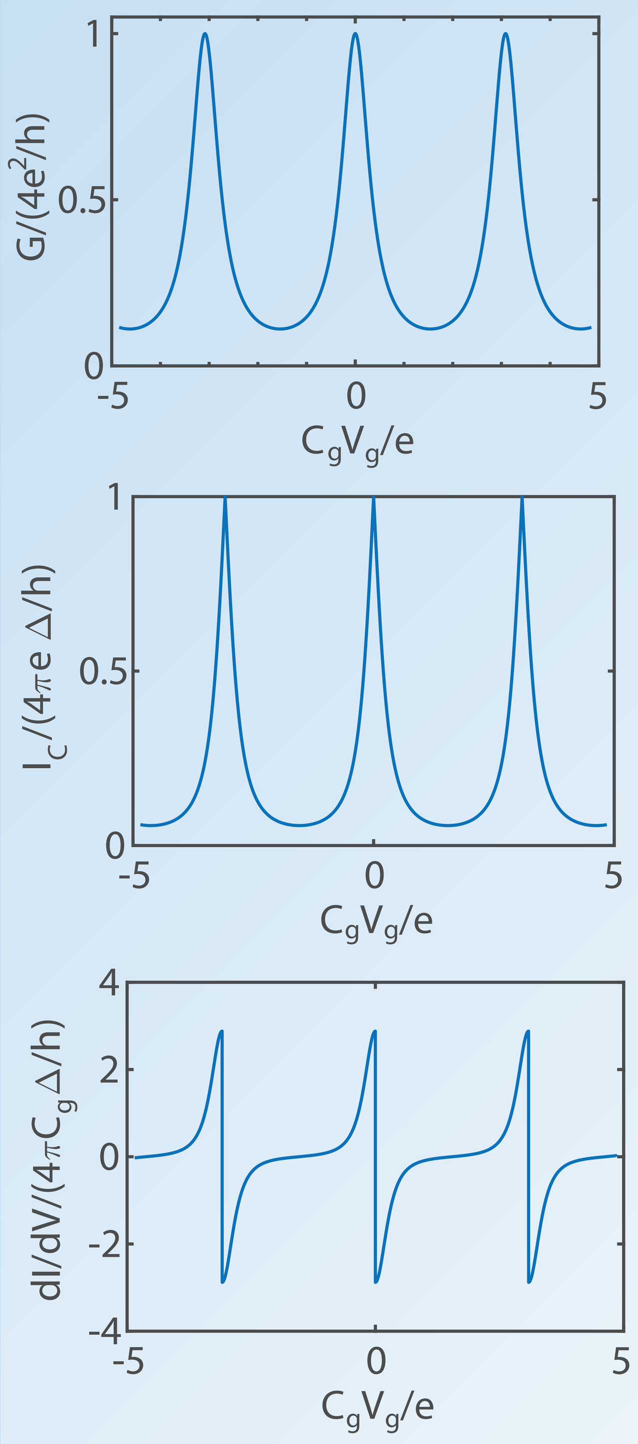




- First device with 5 nm palladium (Pd) cover on top of the MoRe contacts
- Pd should prevent the MoRe from oxidization
- The device shows supercurrent, however, it is very small compared to the device without Pd
- Many features are an indication for multiple tubes



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

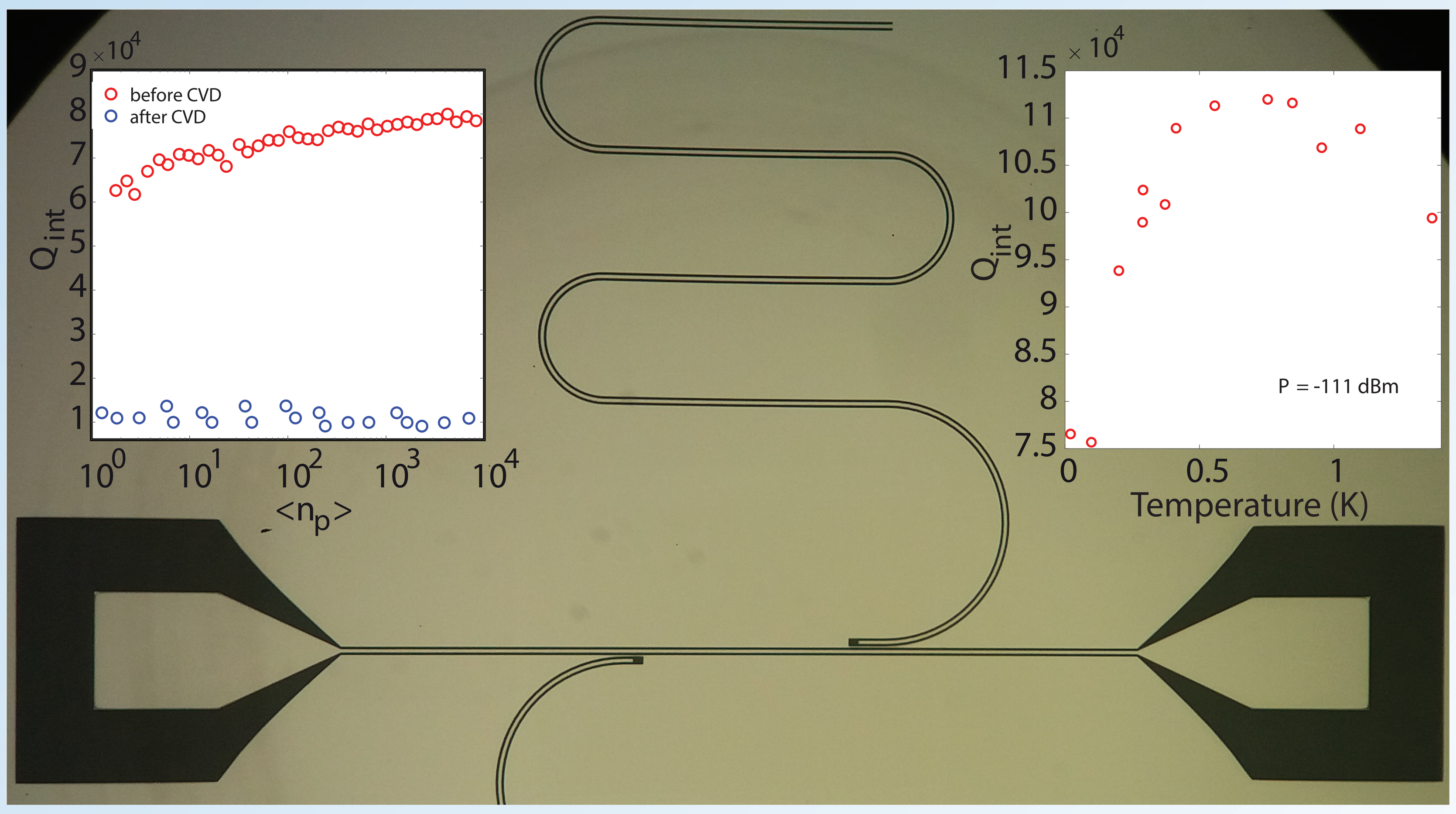
$$\left.\frac{\partial I_C}{\partial V_g}\right|_{max} \approx \frac{4C_g\Delta}{\hbar} = \frac{8\pi L\,\Delta\,\epsilon_0}{\hbar L\,\ln(R_{max}/r_0)} \approx 1\times 10^{-5}\frac{1}{\Omega}$$

and

$$I_C^{max} = \frac{2e\Delta}{\hbar} \approx 100\,\mathrm{nA},$$

with $\Delta = 200\,\mu\mathrm{eV}$, the length of the CNT $L = 1\,\mu\mathrm{m}$, $R_{max} = 0.3$ nm the distance between gate and nanotube and $r_0 = 1$ nm the nanotube radius.

Coupling the CNT to a Cavity



- The readout frequency should be around $f_0 = 5$ GHz and the optimal operation point at $I_C = 100$ nA corresponding to a Josephson energy of $E_J/2\pi\hbar = 48.36$ GHz
- Due to the low charging energy of $E_C/2\pi\hbar = 64.6$ MHz artificial large capacitances $C_s \gg C_g$ are needed
- The coupling between the Qubit and phonon corresponding to the CNT vibration is

$$\frac{g}{2\pi} \approx 8\pi^2\alpha\frac{f_0 V_g \epsilon_0}{e}\frac{L}{R_{max}}x_{zp} = 73\,\mathrm{MHz}.$$

Future outlook

- We demonstrated the working principle of a CNT resonator on Pd/MoRe source/drain pairs
- The combination of suspended CNT and readout cavity introduces new challenges, but also opportunities
- On one hand the contact resistance of the CNT-metal interface is very important for obtaining high critical currents. We will further improve our approach with thin Pd films.
- Another important factor is the placement of the CNT onto the cavity with sufficient accuracy and without degrading the cavity quality factor. We plan to stamp the CNT using a PMMA stamp onto the pre patterned cavity.
- The stamping approach yields another advantage: It enables the characterization of the CNT before transferring resulting in higher yield of useful devices

References

[1] Götz et al., Nanotechnology 27 135202 (2016)
[2] Laiho et al., Appl. Mater. Interfaces, 9 (24) (2017)

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