Carbon nanotubes as ultra-high quality factor mechanical resonators: Supplementary Information

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1 Mass sensitivity

The mass sensitivity is estimated from the data plotted in Figure 4(e) of the main text. In the experiments, the mass sensitivity is limited by the current noise, which has a spectral density $S_I^{1/2} = 0.12\,\mathrm{pA}/\sqrt{\mathrm{Hz}}$. The mass sensitivity $S_m^{1/2}$ can then be calculated as follows: an added mass δm on the nanotube changes the resonance frequency by:

$$\delta\nu_0 = \frac{\partial\nu_0}{\partial m}\delta m = \frac{\nu_0}{2m}\delta m, \tag{S1}$$

where $m = 5.1 \times 10^{-21}$ kg is the mass of a 800 nm long single-walled nanotube with a 1.5 nm radius. When the resonance frequency shifts, the current through the nanotube is modified by:

$$\delta I = \frac{\partial I}{\partial \nu_0}\delta\nu_0 \simeq -\frac{\partial I}{\partial \nu}\delta\nu_0. \tag{S2}$$

The latter approximation, which is valid for a high Q resonator, allows us to relate the change in current to the measured slope of the response function. For the data in Fig. 4(e) the slope of the red line, just right of the jump is $\partial I/\partial\nu = 6.0 \times 10^{-16}$ A/Hz. The mass sensitivity is then calculated from $S_m^{1/2} = \frac{\partial m}{\partial \nu_0}\left(\frac{\partial I}{\partial \nu}\right)^{-1} S_I^{1/2}$, which yields $S_m^{1/2} = 7.0\,\mathrm{yg}/\sqrt{\mathrm{Hz}} = 4.2\,\mathrm{u}/\sqrt{\mathrm{Hz}}$. Here, u is the (unified) atomic mass unit, so it is possible to detect a mass change as small as a single helium atom within one second.

2 Device B

Figure 1 and Figure 2 show measurements on a second device. This device also has a suspended length of 800 nm. From room temperature measurements it is inferred that device B is a large ($E_g/k_b > 300\,\mathrm{K}$) bandgap nanotube as well.

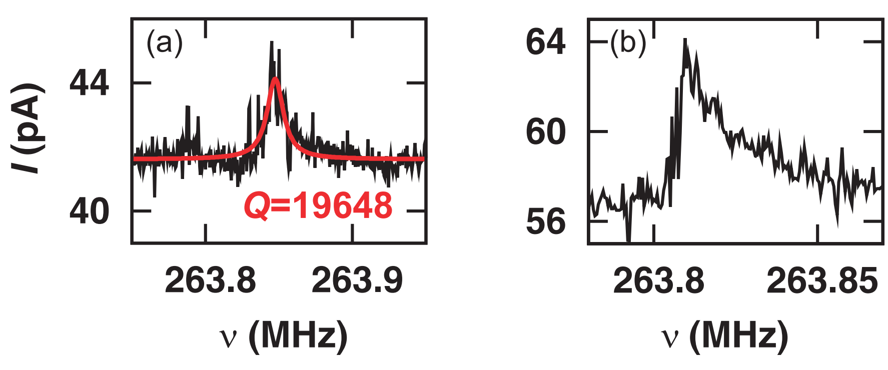

Figure 1: Examples of measured resonances in device B in the linear (a) and non-linear regime (b) at $20\,\mathrm{mK}$. Settings: $V_\mathrm{g} = -4.241\,\mathrm{V}$, $V_\mathrm{sd} = 2.0\,\mathrm{mV}$, RF power $-47\,\mathrm{dBm}$ in (a) and $V_\mathrm{g} = -4.241\,\mathrm{V}$, $V_\mathrm{sd} = 1.5\,\mathrm{mV}$, RF power $-44.5\,\mathrm{dBm}$ in (b).

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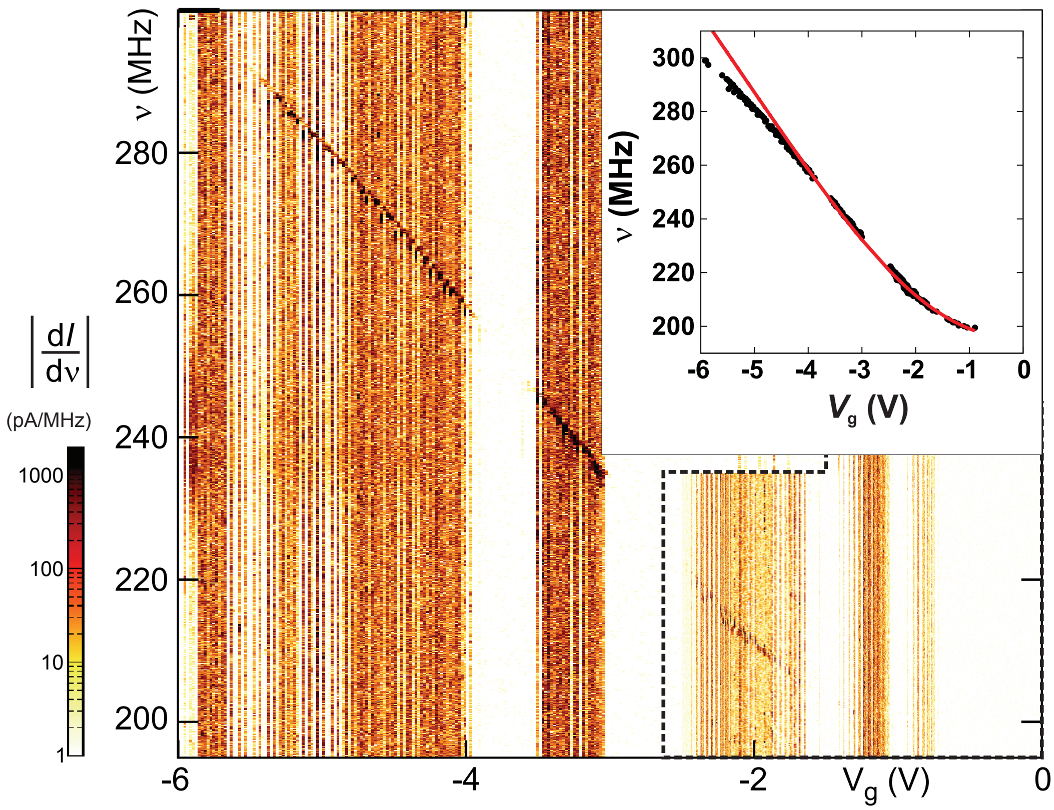

Figure 2: $|dI/d\nu|$ as a function of frequency ν of the ac voltage on the antenna and the dc gate voltage $V_{\rm g}$ on the back-gate electrode for device B. Left of the dashed line a source-drain voltage of $4\,\mathrm{mV}$ was used; on the right side $V_{\rm sd} = 10\,\mathrm{mV}$. The RF power was $-13\,\mathrm{dBm}$ everywhere. Inset: Comparison of the extracted resonance frequency to the continuum model for the bending mode with $\nu_{\rm bending} = 193.7\,\mathrm{MHz}$, $V_{\rm g}^{*} = 4.14\,\mathrm{V}$, $T_0 = 0$ and a horizontal offset of $1.65\,\mathrm{V}$ to account for a shift in the charge neutrality point and the band gap region.