SUPPLEMENTAL MATERIAL

Controlled assembly of graphene sheets and nanotubes: fabrication of suspended multi-element all-carbon vibrational structures

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I. Fabrication process

Figure S1(a) shows an optical image of single layer and multi-layer graphene flakes obtained by mechanical exfoliation. A single or a bilayer graphene flake is selected by measuring the intensity of the reflected light.[1] The flake is shaped in two parallel rectangular plates using reactive ion etching. A dichlorethane solution containing multiwall nanotubes is spin-cast onto the wafer. An atomic force microscopy (AFM) tip is used to position the nanotube across the two graphene plate. The AFM is operated in contact mode. The force of the tip applied onto the surface is maintained low enough so the graphene flake is not scratched. Figure S1(b) shows a series of AFM images recorded during the manipulation. Note that the images show a lot of contamination spots. These contamination spots are removed in the next electron-beam lithography step where each graphene plate is contacted to a pair of Au/Cr electrodes (Fig. S1(c)). The graphene plates and the nanotube are suspended using hydrofluoric acid. Figure S1(d) shows a scanning electron microscope image of a device made from a bilayer sheet upon completion of the fabrication process.

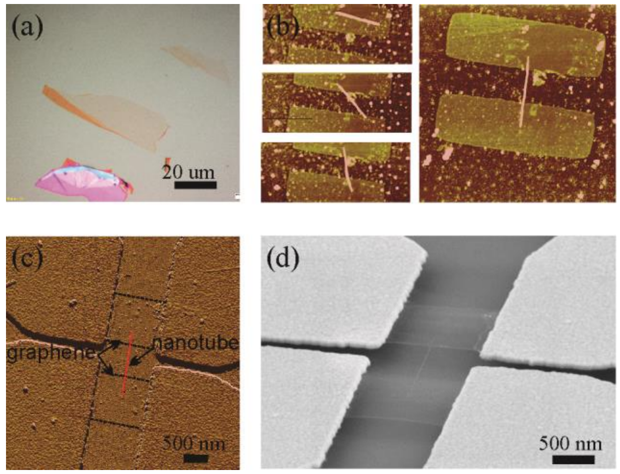

FIG. S1 Fabrication of two graphene resonators coupled by a nanotube. (a) Mechanical exfoliation of graphene onto an oxidized silicon wafer. (b) Manipulation of a nanotube with an AFM tip. (c) Patterning of metal electrodes with electron-beam lithography. (d) Scanning electron microscope image of the device at the end of the fabrication process.

II. Electrical properties

Each graphene plate is electrically contacted by two metal electrodes. Figure S2 shows the conductance of the graphene plates as a function of the voltage V_{BG} applied to the back-gate. The modulation of the conductance is attributed to universal conductance fluctuations (UCF). This layout allows us to electrically detect the mechanical vibrations of the two graphene plates with the frequency-modulation mixing technique (see next section). The mixing current associated to the motion depends on the transconductance dG/dV_{BG}. For each graphene plate there is a specific V_{BG} that maximizes the mixing current. For this reason, Fig. 2(a) in the main text shows mechanical spectra recorded at two different V_{BG}.

The measurements are carried out in a flow cryostat. In order to minimize the consumption of liquid helium, the cryostat is warmed up overnight. The mechanical properties of the device change only slightly from one day to the next. For instance, the resonance frequency changes by less than 10%. However, the changes in the electrical properties are significant. In particular, the universal conductance fluctuations are completely different from one day to the next, and so is the value of V_{BG} for which the mixing current is largest.

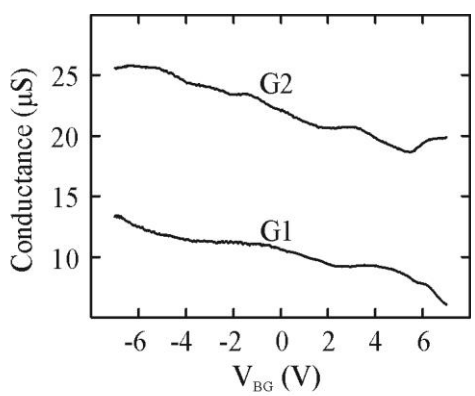

FIG. S2 Conductance versus back-gate voltage for the two graphene plates at 4.3 K.

III. Frequency modulation mixing technique

The devices are actuated and detected using the frequency modulation mixing technique (FM).[2] The motion is detected by applying a FM signal to the source electrode and measuring the low frequency mixing current at the drain electrode. The signal that is applied to the source electrode has the form:

$$V^{FM}(t) = V^{AC}\cos(2\pi f t + (f_{\Delta}/f_{L})\sin(2\pi f_{L} t)),$$

where f is the carrier frequency, f_Δ the frequency deviation, t the time, and f_L a low frequency (typically 671 Hz). The resulting mixing current is measured with a lock-in amplifier at f_L, and is given by

$$I_{mix} = \frac{1}{2}\frac{dG}{dV_{BG}}V_{BG}\frac{C'}{C}V^{AC}f_\Delta\frac{\partial}{\partial f}Re[x_0],$$

where C is the graphene-gate capacitance, C' its derivative with respect to displacement, and $Re[x_0]$ the real part of the motional amplitude.

IV. Resonance frequency versus back-gate voltage

Figure S3 shows the mixing current, as a function of the carrier frequency and V_{BG}, measured on graphene plate 2. These data allow us to extract the resonance frequency as a function of V_{BG} shown in Fig. 2(b) of the main text. The amplitude of the mixing current oscillates as a function of V_{BG} in an aperiodic way due to UCF.

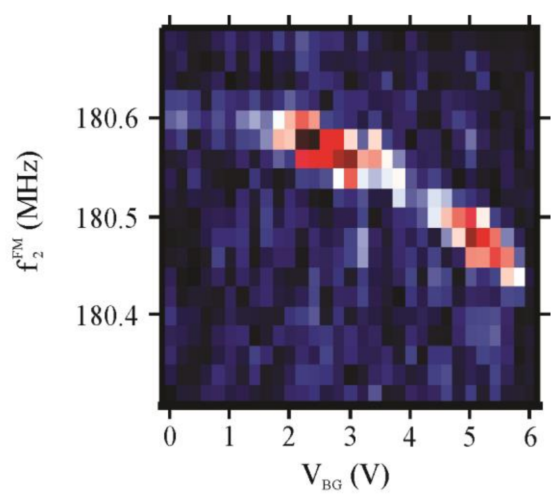

FIG. S3 Mixing current as a function of the carrier frequency and V_{BG}.

V. Finite element simulations

Finite Element method with ANSYS ® release 14.0 has been employed to simulate the eigenmode shapes and the corresponding resonance frequencies of the measured devices. In the FEM simulations, we assume that both ends of the nanotube are firmly attached to the graphene plates because of the large van der Waals interaction. We also assume that the tension and the mass density remain uniform over the plates. We use the geometry of the device measured by AFM (prior to removing the silicon oxide) and the values of the built-in tension and the mass density estimated experimentally (see main text). Figures S4a,b show two eigenmodes, one at 131 MHz and the other at 178 MHz. These values are relatively close to the measured resonance frequencies. The lower-frequency eigenmode has a sizeable amplitude in the upper graphene plate only (Fig. S4(a)). The higher frequency eigenmode features a large displacement of the lower graphene plate (Fig. S4(b)); the motional amplitude of the upper plate can be significant, yet it is not expected to be detected because of the shape of the mode. Indeed, this mode has several nodes, so that the motional amplitude integrated over the upper plate is low. We note that the simulations predict six more modes between the two eigenmodes. However, these additional modes are not expected to be probed in our measurements, since the associated vibrations are localized in the nanotube and/or they have a large number of nodes.

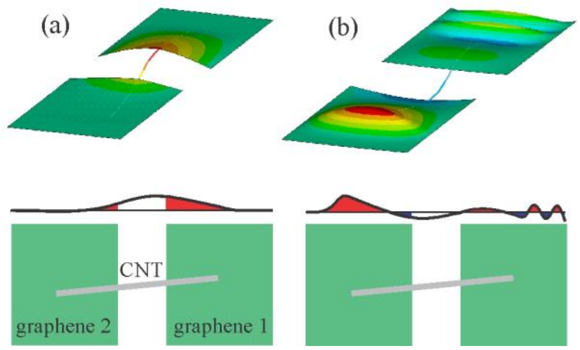

Fig. S4. (a,b) FEM simulation image of the eigenmodes corresponding to the two measured resonances. The lower figures represent the profiles of the eigenmodes together with a (simplified) top view of the device. (Each point of the profile corresponds to the largest displacement along the width of the device.) We perform finite element simulations with ANSYS ® release 14.0 to calculate the modal shapes and modal frequencies using the geometry of the device measured by AFM. The separation between the two graphene plates is 450 nm.

[1] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov, Science **306**, 666-669 (2004).

[2] V. Gouttenoire, T. Barois, S. Perisanu, J. L. Leclerq, S. T. Purcell, P. Vincent, and A. Ayari, Small **6**, 1060-1065 (2010).