Supporting Information

Thickness of suspended epitaxial graphene (SEG) resonators:

Graphene thickness was estimated using an atomic force microscope (AFM) by going over the step edge from SiC to graphene. Graphene on SiC was patterned into strips using an oxygen plasma etch. Measurements were conducted by moving the AFM tip from a graphene-free region of SiC to graphene on SiC. However, thickness determination before the Ar/H_2 anneal was not straightforward because of the following two reasons: 1) oxidation of SiC upon exposure to the oxygen plasma 2) presence of steps on the SiC surface. It was found from AFM measurements that the region from which graphene had been etched away was higher than the region where graphene was present. This is attributed to a thin oxide layer forming on top of the exposed SiC after removal of graphene by the oxygen plasma. The Ar/H_2 anneal caused the oxidation layer to be removed and AFM measurements performed post-anneal suggest a graphene thickness no greater than 2 nm. For the sake of calculations in this work, we assume a graphene thickness of 1 nm. This estimate that the graphene is only a few monolayers thick is further corroborated by the fact that the 2D Raman peak of the suspended graphene can be fit very well by a single Lorentzian[1] (Fig. 2(d) of manuscript).

Critical Buckling Load for Graphene Resonators:

The critical buckling stress for a beam of length L and thickness t is given by[2] $\sigma_{cr} = \dfrac{\pi^2 E t^2}{3L^2}$, where E is the Young's modulus of the material. The corresponding strain is $\varepsilon_{cr} = \dfrac{\pi^2 t^2}{3L^2}$. For a graphene beam of length 10 μm and thickness 1 nm, the critical strain for buckling is 3.3×10^{-6} %, which is five orders of magnitude smaller than the strain estimated from Raman spectra. So, we expect the graphene beams to be buckled.

Calculation showing increased resonance frequency of a beam with inverted U-shaped cross-section:

A schematic of the inverted U-shaped cross-section is shown in Fig. 1 (a). *w* and *t* are the width and the thickness of the beam respectively, while *y* denotes the length of the side-flange. The position of the neutral axis is given by

$$\bar{y} = \frac{(t(w-2y-2t))\left[\dfrac{t}{2}\right] + 2\times(yt)\left[\dfrac{y}{2}\right]}{t(w-2y-2t)+2\times(yt)}$$

The moment of inertia of the beam about the neutral axis can be calculated by summing the moments of inertia of three smaller beams (two vertical and one horizontal), which the cross-section may be assumed to be comprised of.

$$I = \left[\frac{1}{12}(w-2y-2t)t^3 + (w-2y-2t)t\left(\bar{y}-\frac{t}{2}\right)^2\right] + 2\times\left[\frac{1}{12}ty^3 + ty\left(\bar{y}-\frac{y}{2}\right)^2\right]$$

The fundamental resonance frequency of the beam is then obtained using[3]

$$f_0 = \frac{4.73^2}{2\pi}\frac{1}{L^2}\sqrt{\frac{E}{\rho}}\sqrt{\frac{I}{wt}}$$

The resonator shown in Fig. 1(b) is 20 μm long and from standard beam theory for a beam under no tension, it is expected to have a fundamental resonance at 54.9 kHz. The observed resonance for the device is at 12.7 MHz. The beam has side-flanges which cause it to be narrower in the center than near the clamps. It can also be seen that the cross-section of the beam varies over its length. However, as a simplifying approximation, we model the device with a uniform U-shaped cross-section, as described above. The length of the side-flange at the center of the beam can be estimated as (1572 – 836.7)/2 nm = 367.6 nm. Because of the non-uniform nature of the cross-section, we assume y to be uniformly half of this value in our simple approximation i.e. y = (367.6/2) nm = 183.8 nm. Assuming this value of y and using the known dimensions of the beam and material parameters of bulk graphite, the calculated value for f_0 = 8.97 MHz. Hence, we propose that this simple model can roughly account for the observed increase in stiffness of the resonator.

Nano-indentation experiments using AFM cantilever:

Nano-indentation experiments were performed using a DI 3100 AFM. The cantilevers used for the experiment were calibrated on an Asylum Research MFP-3D AFM using a thermal noise method. The spring constants of the cantilevers employed were measured to be 9.83 N/m and 2.77 N/m. Force-displacement curves for some SEG devices showed sudden changes in the tip deflection, suggesting either conformational modification of the device or tip slip[4]. These were not considered in the data analysis.

Figure Caption

Figure 1. (a) Model of a beam with an inverted U-shaped cross-section (b) SEM image of a SEG resonator device. The device is narrower in the center because of the side-flanges.

References:

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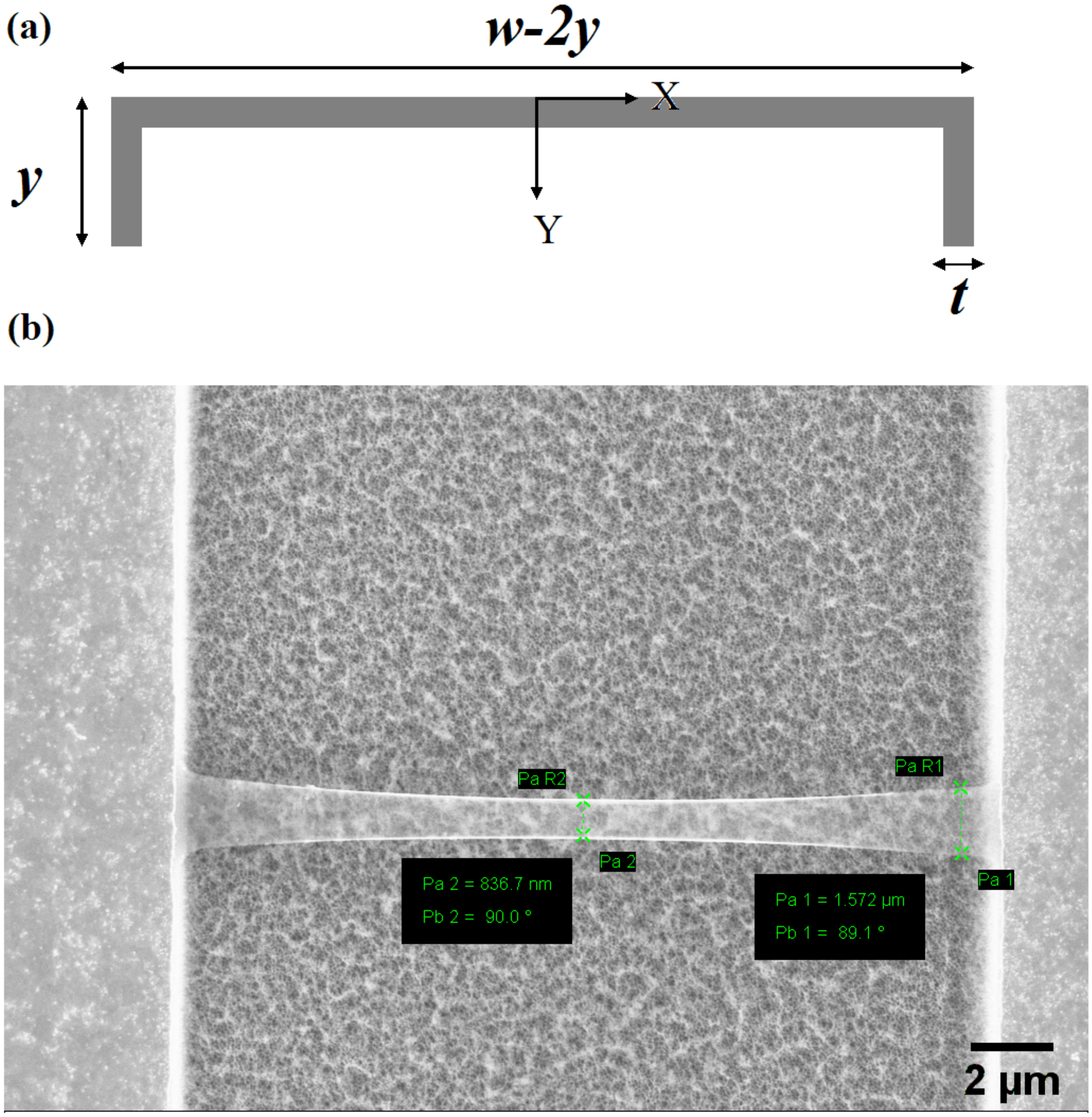
(a)
w-2y
X
y
Y
t
(b)
Pa R2
Pa R1
Pa 2
Pa 1
Pa 2 = 836.7 nm
Pb 2 = 90.0 °
Pa 1 = 1.572 µm
Pb 1 = 89.1 °
2 µm

Figure 1