Supporting Information: Mechanical mode imaging of a high-Q hybrid hBN/Si_3N_4 resonator

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COMSOL simulations

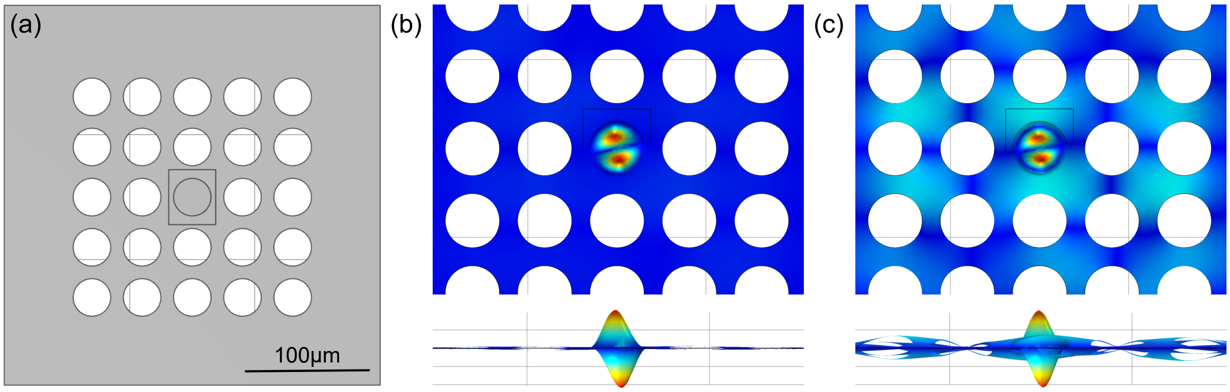

Figure S1: (a) Simplified geometry used for our simulations. (b),(c) Top and side view of two copies of hBN drum modes with different degrees of hybridization with the Si_3N_4 membrane.

For the geometry of the COMSOL simulation we approximate the hBN flake as a rectangle covering the central hole of the Si_3N_4 membrane, while the Si_3N_4 membrane itself could be accurately reproduced due to its well-defined shape. The thickness of the membrane is 200 nm and that of the flake is 48 nm in accordance with the AFM measurement shown in Fig.1(c) of the main text.

We match the simulated frequency of the fundamental mode of the hBN drum to the one we observe experimentally using the pre-tension of the flake. The reported values for the Young's modulus of hBN vary greatly;[S1,S2] if we chose the average value of 392 GPa reported in Ref. S1, we have to set the pre-tension to 0.36 N/m. However, for a Young's modulus of 700 GPa and a pre-tension of 0.15 N/m, which is still within the range of reported values and closer to theoretical predictions,[S3] we find a better agreement towards higher order modes. The stoichiometric Si_3N_4 membrane has a tailored stress of 900 MPa.

The mode shapes are evaluated as a shell instead of a membrane to take bending stiffness into account which is expected to play a role given the thickness of our hBN flake.[S1] We introduce asymmetry into the system with a 1% deviation from the square shape of the Si_3N_4 membrane and the rectangular shape of the hBN flake.

Force and mass sensitivity estimates

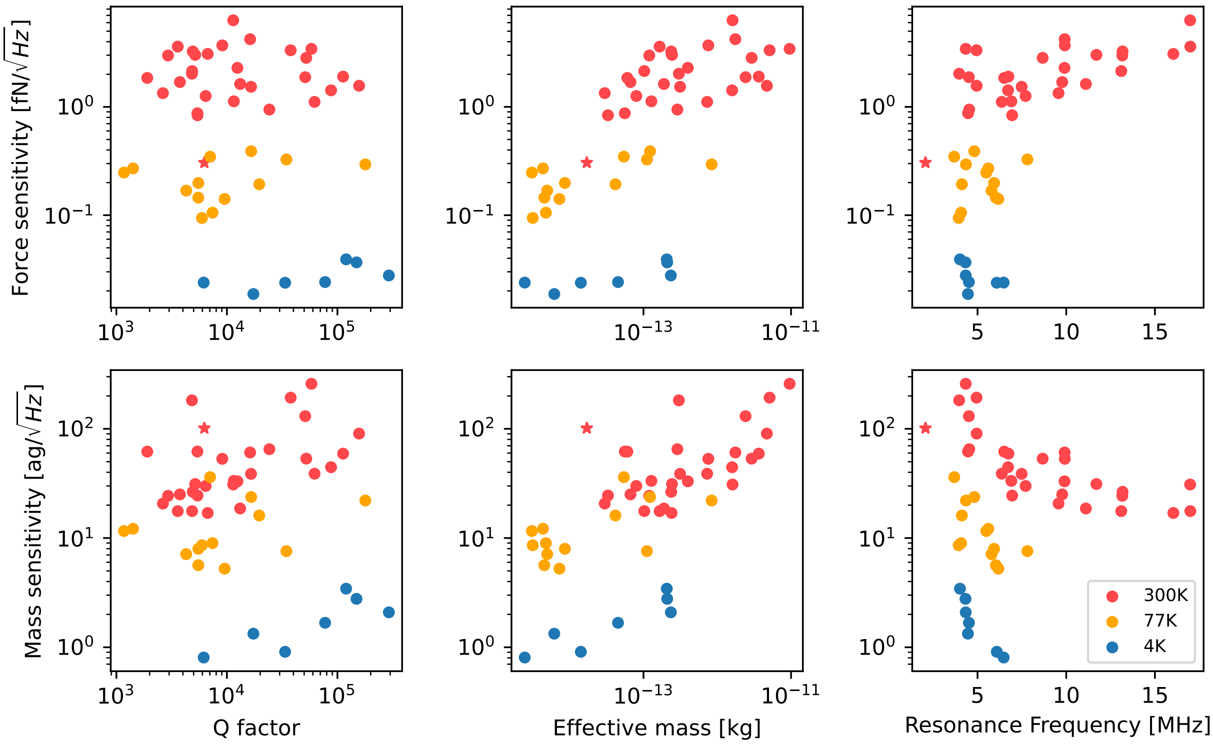

Figure S2: Force sensitivity (mass sensitivity) shown vs. Q, m^* and resonance frequency in the top (bottom) row. The star shaped marker shows the fundamental mode of the hBN drum.

The force and mass sensitivities in units of $[N/\sqrt{Hz}]$ and $[kg/\sqrt{Hz}]$ are given by

$$S_f^{-1/2}(\omega) = \sqrt{4k_BT\Gamma m^*} \tag{1}$$

$$S_m^{-1/2}(\omega) = \sqrt{2k_BT\Gamma m^*}\frac{2}{x_0\omega_0^2} \tag{2}$$

with x_0 the oscillation amplitude (assumed to be 1 nm for the results shown in Fig. S2).

In Fig.S2 the resulting sensitivities for the mechanical modes of the hBN drum are plotted. For the force sensitivity at room temperature, the best values are predicted for the fundamental mode. This indicates that for our system, the gain in Q does not outweigh the increase in m^*, since the fundamental mode of hBN has the lowest effective mass. The mass sensitivity has an additional factor proportional to $\frac{1}{x_0\omega_0^2}$, giving it a stronger dependence on frequency. Nevertheless, no systematic improvement (decrease) in sensitivity is observed with increasing hybridization. If hybridization were beneficial to mass sensitivity in our device, we would expect, for example, mass sensitivity at a constant temperature to improve (decrease) as a function of increasing effective mass, since stronger hybridization tends to increase the effective mass. Instead the opposite trend is apparent in Fig.S2.

Going to 77 K and then to 4 K not only improves the sensitivities due to their temperature dependence, but also because of the reduction of m^* for the smaller modes in the bulged membrane.

Mechanical properties of the Si_3N_4 membrane

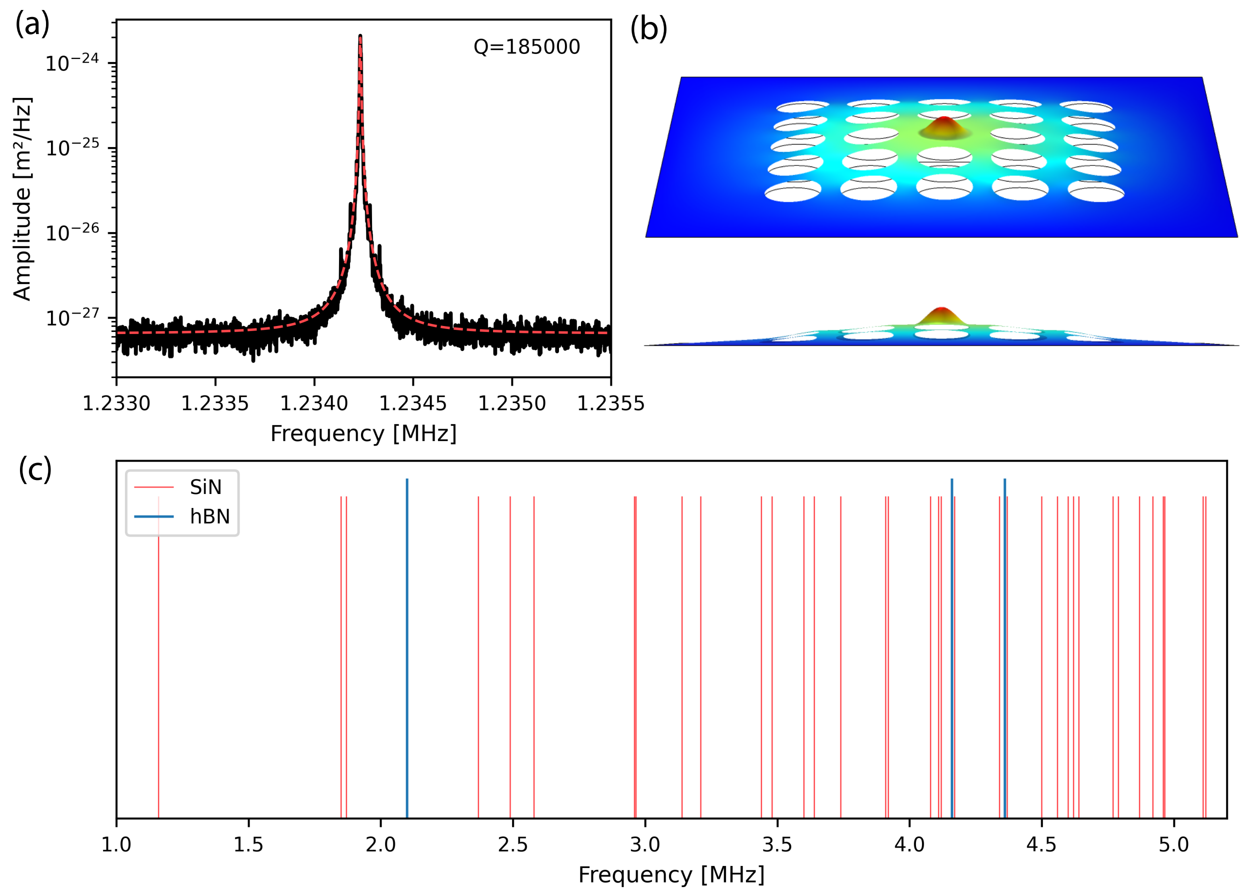

Figure S3: (a) Thermal motion of the fundamental mode of the Si_3N_4 membrane. (b) COMSOL simulation of the mode shown in (a). (c) Predicted frequencies for the mechancial modes of the isolated Si_3N_4 membrane (orange) and the isolated hBN drum (blue).

The fundamental mode of the Si_3N_4 membrane has a Q of 1.8×10^5 at room temperature. This mode is lower in frequency than the fundamental mode of hBN by almost a factor of two, so no hybridization is expected. This shows that the highest Q of hybridized modes shown in the main text, of around 1.5×10^5 is not far from this highest value. Before the transfer of a hBN flake, we typically measure Qs of 5×10^5 for the fundamental mode. For higher order modes, the values range from 2×10^5 to 5×10^5. This shows that the Q of the Si_3N_4 membrane is reduced by our transfer process, but it remains around the same order of magnitude.

In Fig.S3(b) we show the simulated mode shape for the fundamental mode of the Si_3N_4 membrane. Apart from the expected overall shape, we can observe that the hBN still interacts with this mode by effectively increasing the amplitude due to its different mechanical properties. In Fig.S3(c) we show why densely packed the frequency spacings become past 3 MHz for the Si_3N_4 membrane, explaining how the fundamental mode of the hBN drum is not hybridized, while the higher order modes tend to be hybridized to varying degrees.

References

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(S2) Cartamil-Bueno, S. J.; Cavalieri, M.; Wang, R.; Houri, S.; Hofmann, S.; van der Zant, H. S. J. Mechanical Characterization and Cleaning of CVD Single-Layer h-BN Resonators. *1*, 16

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