Supplemental Document

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Macroscopic laser pulling based on the Knudsen force in rarefied gas: supplement

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Supporting information

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SEM image of the bulk cross-linked graphene material

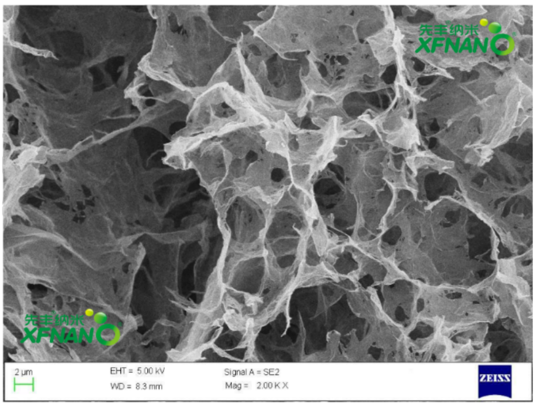

Fig. S1. SEM image of the bulk cross-linked graphene material we used (provided by the commercial corporation XFNANO).

Reflectivity and transmissivity of the bulk cross-linked graphene material

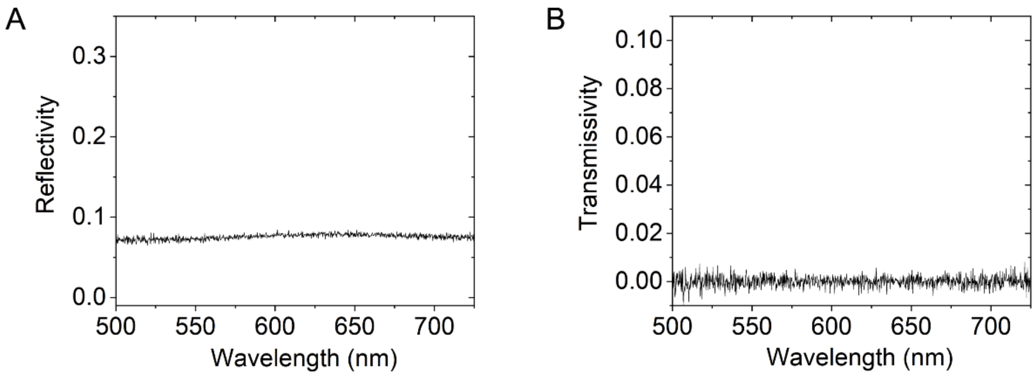

Fig. S2. Reflectivity and transmissivity of the bulk cross-linked graphene material. (A) Reflectivity of the bulk cross-linked graphene material at different laser wavelength. (B) Transmissivity of the bulk cross-linked graphene material at different laser wavelength.

The effect of laser power on the pulling force

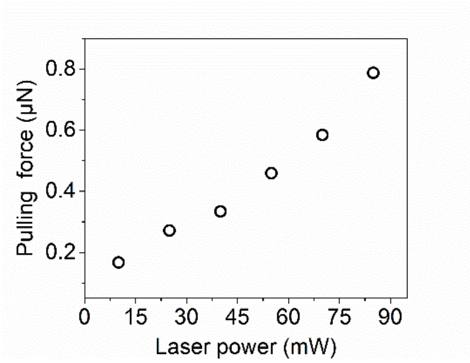

Fig. S3. The relation between the laser power (10 mW ~ 85 mW) and the pulling force. The laser wavelength is 488 nm.

Estimation of the Knudsen force

Generally, for $Kn > 10$, the free molecular flow assumption can reasonably describe the gas behavior, in which case, the Knudsen force can be calculated by the following equation [1]:

$$F = \frac{P}{2} A \left(\sqrt{\frac{\alpha_E T_h + (1-\alpha_E) T_g}{T_g}} - \sqrt{\frac{\alpha_E T_c + (1-\alpha_E) T_g}{T_g}} \right) \qquad \text{(S1)}$$

where T_h and T_c are the hot and the cold side temperatures, respectively, T_g is the free stream gas temperature, A is the area of the hot or cold side of the object, and α_E is the energy accommodation coefficient.

For air pressure of 5 Pa in our experiment, Kn is about 0.2 ~ 0.3. Although the free molecular flow assumption can not be strictly satisfied in our experiment, the pulling force might be roughly estimated by Equation S1. Considering the laser power we used is small (several to tens of milliwatt) and the laser beam is unfocused, thus the temperature rise is modest. Assuming 330 K < T_h < 400 K, $T_c = T_g = 300$ K, and $\alpha_E = 1$ [2], the theoretically calculated laser pulling force based on Equation (S1) ranges from 1.5 μN to 4.7 μN, which agrees with the measuring result (0.8 μN) in the same order of magnitude.

Visualization S1

Visualization S1 presents the macroscopic laser pulling of the CLG-SiO_2 sample with wavelength of 532 nm at the air pressure of 5 Pa. The laser power irradiated on the material is 60 mW and the light is unfocused. Counterclockwise rotation of the torsional pendulum is observed and the macroscopic CLG-SiO_2 sample is pulled towards the light source.

Visualization S2

Visualization S2 presents the macroscopic laser pulling of the CLG-SiO_2 sample with wavelength of 488 nm at the air pressure of 5 Pa. The laser power irradiated on the material is 85 mW and the light is unfocused. Counterclockwise rotation of the torsional pendulum is observed and the macroscopic CLG-SiO_2 sample is pulled towards the light source.

Visualization S3

Visualization S3 presents the macroscopic laser pulling of the CLG-SiO_2 sample with wavelength of 360 nm at the air pressure of 5 Pa. The laser power irradiated on the material is 13 mW and the light is unfocused. Counterclockwise rotation of the torsional pendulum is observed and the macroscopic CLG-SiO_2 sample is pulled towards the light source.

Visualization S4

Visualization S4 presents the laser irradiation of the CLG-SiO_2 sample with wavelength of 532 nm at normal pressure. The laser power irradiated on the material is 60 mW and the light is unfocused. The CLG-SiO_2 sample is motionless and the macroscopic laser pulling is negligible.

Visualization S5

Visualization S5 presents the macroscopic laser pulling of the CLG-SiO_2 sample with wavelength of 488 nm at the air pressure of 5 Pa. The laser power irradiated on the material is 17 mW and the light is unfocused. Counterclockwise rotation of the torsional pendulum is observed and the macroscopic CLG-SiO_2 sample is pulled towards the light source. The maximum rotation angle of the torsional pendulum is about 1°.

Visualization S6

Visualization S6 presents the macroscopic laser pulling of the CLG-SiO_2 sample with wavelength of 488 nm at the air pressure of 5 Pa. The laser power irradiated on the material is 34 mW and the light is unfocused. Counterclockwise rotation of the torsional pendulum is observed and the macroscopic CLG-SiO_2 sample is pulled towards the light source. The maximum rotation angle of the torsional pendulum is about 2°.

Visualization S7

Visualization S7 presents the macroscopic laser pulling of the CLG-SiO_2 sample with wavelength of 488 nm at the air pressure of 5 Pa. The laser power irradiated on the material is 51 mW and the light is unfocused. Counterclockwise rotation of the torsional pendulum is observed and the macroscopic CLG-SiO_2 sample is pulled towards the light source. The maximum rotation angle of the torsional pendulum is about 3.8°.

Visualization S8

Visualization S8 presents the macroscopic laser pulling of the CLG-SiO_2 sample with wavelength of 488 nm at the air pressure of 5 Pa. The laser power irradiated on the material is 68 mW and the light is unfocused. Counterclockwise rotation of the torsional pendulum is observed and the macroscopic CLG-SiO_2 sample is pulled towards the light source. The maximum rotation angle of the torsional pendulum is about 5.8°.

References

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