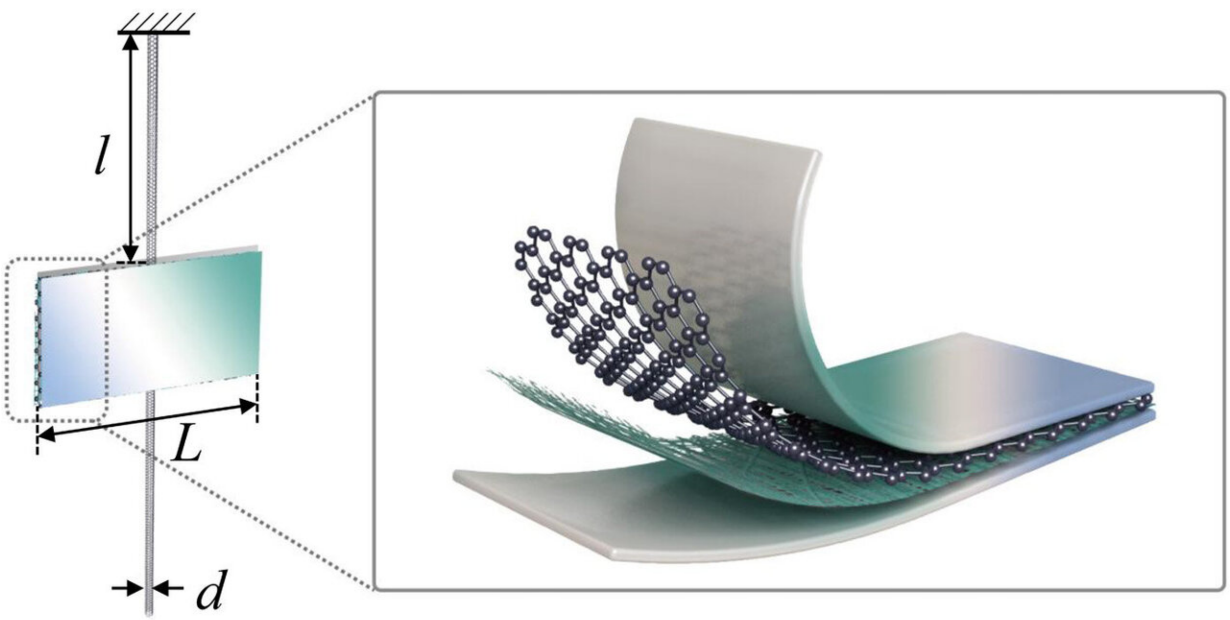
On-chip torsion balance with femtonewton force resolution at room temperature

March 25 2021, by Thamarasee Jeewandara

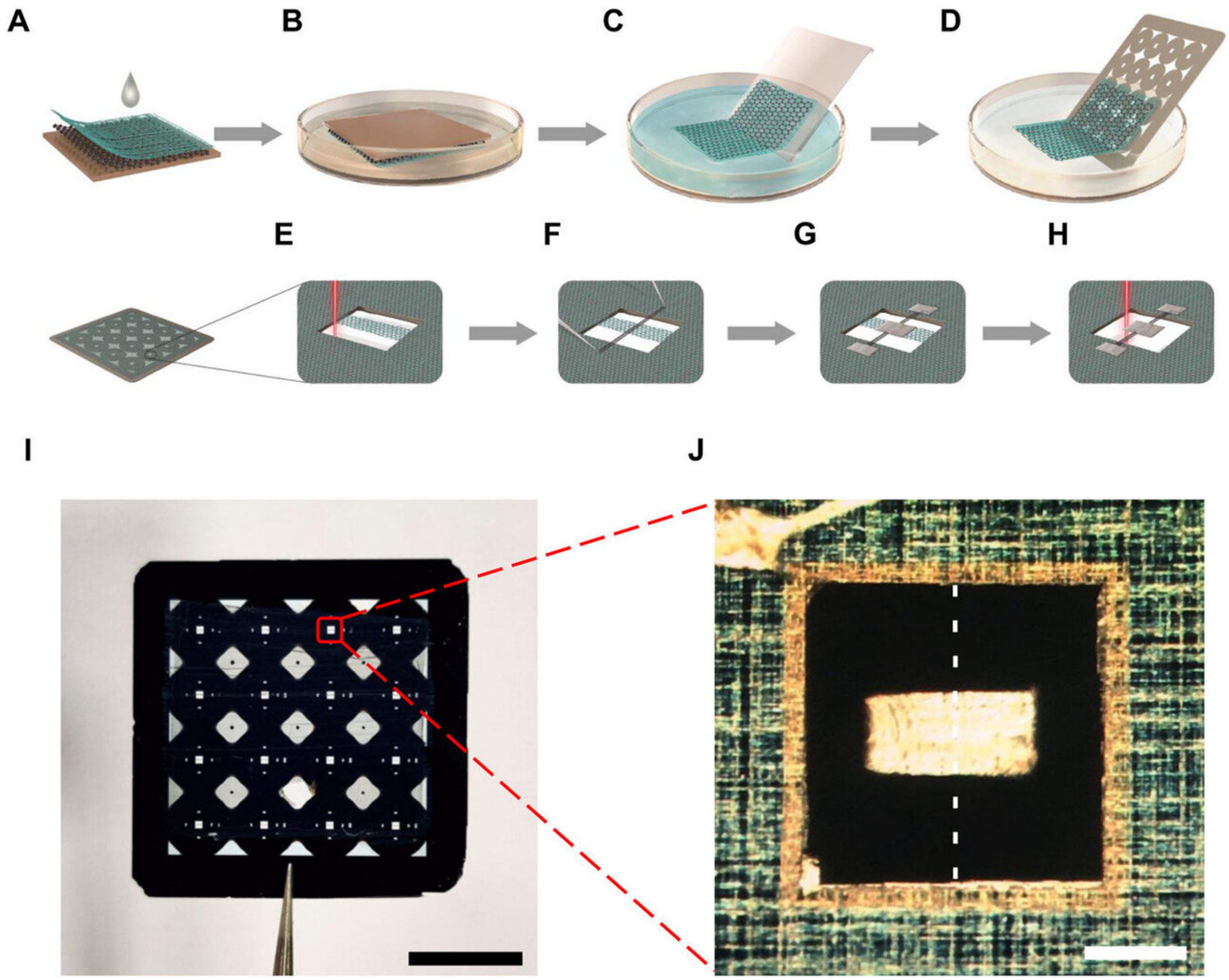


Schematic illustration of the torsion balance unit. It consists of an Al/graphene/CNT/Al mirror with beam length L suspended by an individual CNT with diameter d and suspension length l. Credit: Science Advances, doi: 10.1126/sciadv.abd2358

The torsion balance contains a rigid balance beam suspended by a fine thread as an ancient scientific instrument that continues to form a very sensitive force sensor to date. The force sensitivity is proportional to the lengths of the beam and thread and inversely proportional to the fourth power of the diameter of the thread; therefore, nanomaterials that support the torsion balances should be ideal building blocks. In a new report now published on *Science Advances*, Lin Cong and a research team in quantum physics, microelectronics and nanomaterials in China have detailed a torsional balance array on a chip with the highest sensitivity level. The team facilitated this by using a carbon nanotube as the thread and a monolayer graphene coated with aluminum films as the beam and mirror. Using the experimental setup, Cong et al. measured the femtonewton force exerted by a weak laser. The balances on the chip served as an ideal platform to investigate fundamental interactions up to zeptonewton in accuracy.

A modern role for ancient scientific instruments

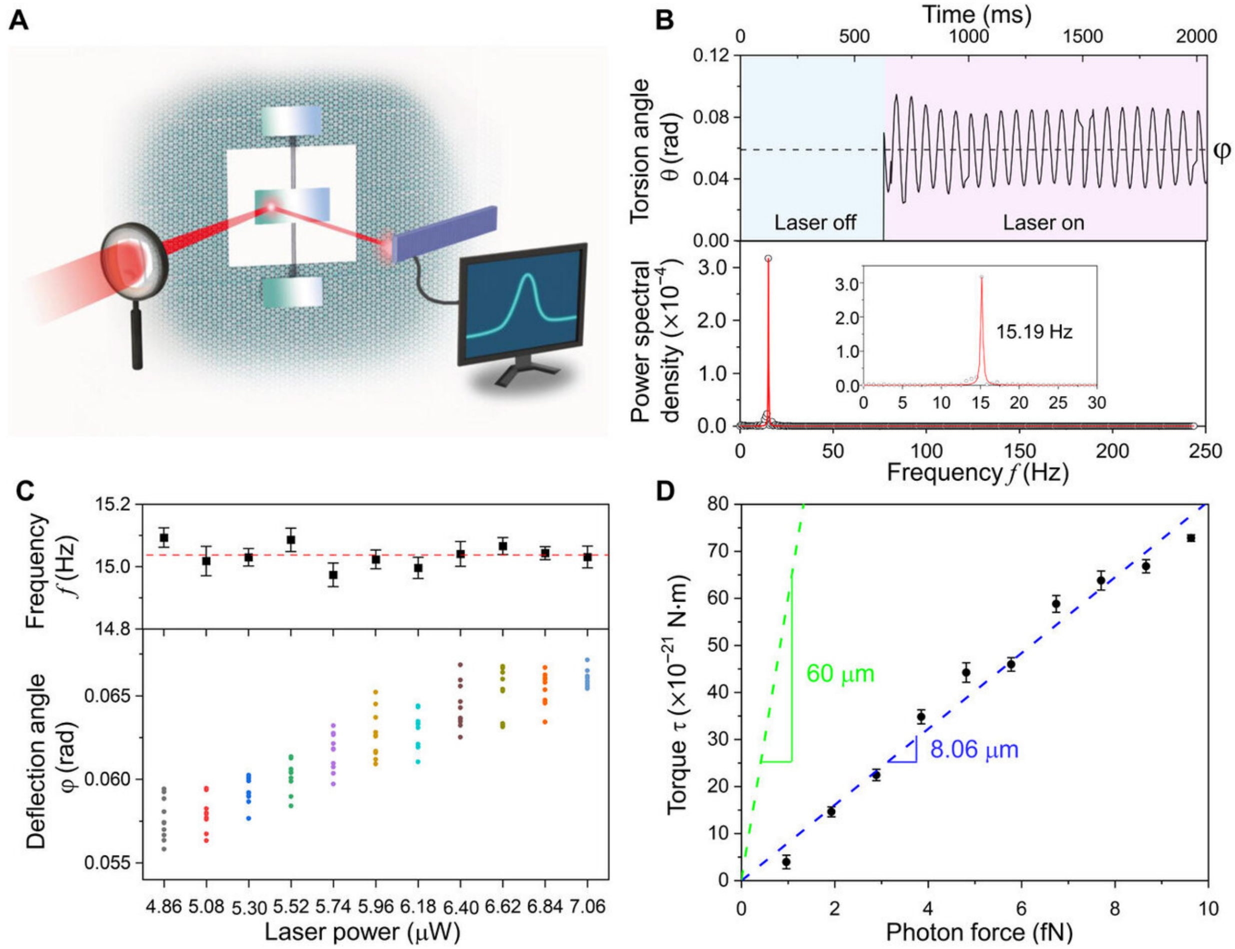
The torsion pendulum is an ancient scientific instrument used to discover Coulomb's law in 1785 and to determine the density of Earth in 1798. The instrument is useful across a range of applications including existing scientific explorations of precisely determining the gravitational constant . The most efficient method to achieve high sensitivity in the setup is by reducing the diameter of the suspension thread as much as possible. For instance, in 1931, Kappler et al. used a centimeters-long thread to develop a highly sensitive torsion balance to set a record for a hitherto unattained intrinsic force sensitivity. At present, carbon nanotubes form one of the strongest and thinnest materials known. In this work, the team synthesized ultra-long carbon nanotubes (CNTs) and large-area graphene to substantially increase the lengths of the balance beam and suspension thread to significantly improve the sensitivity of the instrument. The device development method was compatible with semiconductor processing for incorporation into a 4 by 4 array on a chip.



The fabrication process of the CNT torsion balance. (A) Superaligned CNT film stuck on graphene/Cu foil after alcohol infiltration. (B) Inverted CNT/graphene/Cu-foil three-layer structure floating on corrosive solution. (C) GCF rinsed with deionized water after etching Cu away. (D) GCF transferred to a substrate. (E) Laser-trimmed GCF stripe acting as the skeleton of the mirror. (F) Substrate assembled with an individual CNT. (G) Semifinished torsion balance with 10-nm Al film deposited on both sides of the GCF stripe. (H) CNT torsion balance ultimately obtained by cutting off the connecting parts. (I) Si substrate with a 4 × 4 array of CNT torsion balances fabricated after step (E). Scale bar, 5 mm. Photo credit: Kaili Jiang, Tsinghua University. (J) Optical microscope photograph of a torsion balance after completing the fabrication process. The dashed line indicates the position of the CNT thread. Scale bar, 100 μm. Credit: Science Advances, doi: 10.1126/sciadv.abd2358

Designing and developing the torsion balance and torsion balance array

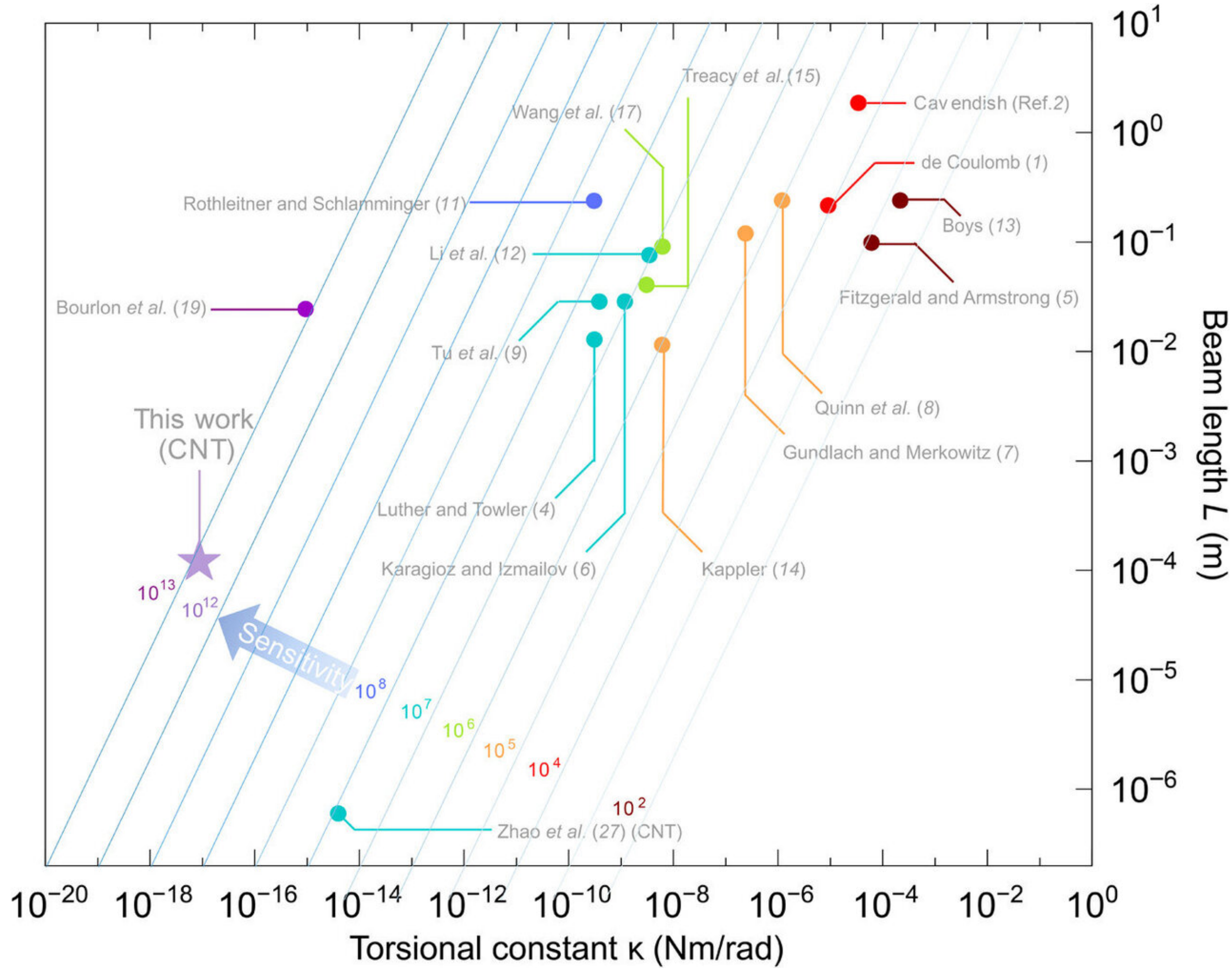
During the design process, Cong et al. selected an individual carbon nanotube with a diameter of a few nanometers to form the thread, for suspension as an ultralight beam made of monolayer graphene coated with aluminum films. The extremely low moment of inertia of the instrument reduced the measurement time to sub-seconds at room temperature compared to the Kappler instrument, which took hours. The development process of the torsion balance array included the formation of a free-standing graphene CNT-film, which Cong et al. transferred onto a prefabricated silicon wafer array. The scientists then transferred an individual carbon nanotube (CNT) to a graphene-CNT (GCF) covered substrate as a suspension thread. They then deposited a thin layer of aluminum on both sides of the substrate to obtain a high-reflectivity mirror and removed parts of the graphene-carbon nanotube using a laser. Ultimately, the ultrathin mirror appeared to float in air due to the invisibility of the CNT thread under an optical microscope.



The optical measurement setup and typical measurement results of CNT torsion balance #1. (A) Schematic diagram of the optical readout system of the torsion balance. (B) Dynamic response of the torsion balance to the optical pressure of a laser beam at a power of 4.86 μW (top) and the corresponding fast Fourier transform (FFT) power spectra (bottom; black circle represents the FFT data, and red line is the curve fitting). (C) Equilibrium deflection angles and frequency against the laser power. The error bar of the top panel is obtained from statistics on 10 independent measurements. (D) Torque versus incident photon force. The effective lever length in the measurement is 8.06 μm. The green dashed line is the theoretical torque-force relation at the full lever length of L/2 = 60 μm. Credit: Science Advances, doi: 10.1126/sciadv.abd2358

Measurements and sensitivity characterization.

To overcome the influence of air currents, Cong et al. sealed the CNT torsion balance in a vacuum chamber and added the chamber on to an optical workstation with a high-performance laminar flow isolator to isolate the vibration and mechanical noise from the environment. During the measurements, the scientists stopped the dry pump and turbo pump of the system and only maintained the ion pump to retain vacuum activity. For the optical measurement, the team focused a laser beam with power of a few microwatts to exert photon pressure and cause the torsion balance to rotate at a small angle around the carbon nanotube (CNT) thread. They then measured the induced angle with a line array charge-coupled device (CCD) sensor to detect the position of the reflected light. The torsional potential energy of the mirror agreed with the theoretical values predicted by the Brownian motion theory. To understand the performance of the balance, Cong et al. conducted optical readouts for 11 different laser powers across 10 different sites. The average values of the torsional oscillation frequencies did not change with laser power. The carbon nanotube torsion balance could measure the weak force with femtonewton resolution, and the laser power could be reduced further to avoid out-of-range deflections. Further reductions of laser power severely affected the angle measurement; the researchers therefore suggest using a second probing laser beam to detect the deflection angle when measuring sub-femtonewton forces exerted by a weaker laser light.



The comparison map of CNT torsion balances and classical torsion balances. In addition to displaying the measured torsional constant κ and beam length L of each experiment, the sensitivity of the apparatus defined by the deflection angle produced by 1 N is also shown, which can be obtained from L/2κ. The parallel lines colored from light blue to dark blue indicate orders of magnitude of sensitivity ranging from 2 to 13. The experiments are grouped and separated by color according to the order of magnitude of sensitivity. Credit: Science Advances, doi: 10.1126/sciadv.abd2358

Outlook

In this way, Lin Cong and colleagues provided a reliable method to facilitate torsion balance to make it attractive for on-chip applications. The team improved the performance of the carbon nanotube torsion balance using a small-diameter carbon nanotube as a suspension thread. The expected zeptonewton force resolution could break the record of results obtained at ultralow temperature as an important breakthrough in the field of weak force measurement. The torsional angle of the carbon nanotube can be continuously adjusted to influence the electron transport properties produced via torsional strain across a wide range. The current study is preliminary and can be improved further. The on-chip carbon nanotube (CNT) tension balances detailed in this work offered femtonewton resolution based on an individual carbon nanotube as the suspension thread and an aluminized graphene-CNT (GCF) as the balance beam and mirror. The high sensitivity and simple fabrication of the CNT torsion balance will allow new fundamental research to explore weak effects and determine new laws of physics.

More information: Cong C. et al. On-chip torsion balances with femtonewton force resolution at room temperature enabled by carbon nanotube and graphene, *Science Advances*, 10.1126/sciadv.abd2358

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Citation: On-chip torsion balance with femtonewton force resolution at room temperature (2021, March 25) retrieved 9 April 2024 from https://phys.org/news/2021-03-on-chip-torsion-

femtonewton-resolution-room.html

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