demonstrating how nanostructuring alone provides significant performance enhancements relative to conventional batteries. The all-in-one nanopore battery retains 95% of its energy when discharged in 12 minutes, and 46% when discharged in ~25 seconds (as a comparison, a conventional battery would provide very little energy under a 25-second discharge). In contrast to many nanostructured batteries, which show considerable capacity fade with cycling, the all-in-one battery retains most of its capacity over 1,000 charge–discharge cycles, indicating that nanostructuring is compatible with long cycle life batteries.

Although Rubloff and colleagues report exceptional rate characteristics and stability for their all-in-one battery, there is still a lot to learn before these findings can be translated into the design of nanostructured batteries with the immense capacities that are needed for commercial applications such as for transport and the energy grid. Developing such batteries will be a significant challenge for the field, and questions remain. In particular, can the findings from the all-in-one battery concept be applied to a commercially scalable electrode design? We suspect the answer is yes, given the creativity of the battery community. However, fabricating electrodes containing the appropriately nanostructured elements on the many ton scale will be difficult. Nevertheless, this fundamental work provides a variety of insights into the potential of battery miniaturization. ❒

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NANOMECHANICS

Nanotubes resound better

Advanced measurement techniques combined with a tightly controlled noise environment have enabled the creation of carbon nanotube-based mechanical resonators with quality factors of up to five million.

Ilya Khivrich and Shahal Ilani

Nanoscale mechanical resonators can be used as extremely sensitive force and mass detectors and have promising prospects as devices operating in the quantum mechanical regime. In all such applications, their performance depends crucially on the mechanical quality factor, Q — the ratio between the energy stored in the resonator and the energy lost in a single oscillation cycle. Writing in *Nature Nanotechnology*, Adrian Bachtold and collaborators at the Institut de Ciencies Fotoniques in Barcelona and Michigan State University demonstrate a significant improvement in the quality factor of carbon nanotube-based mechanical resonators to a record value of 5 million (ref. 1), paving the way for ultrasensitive mass and force detection, and for the development of quantum bits with long coherence times based entirely on mechanical motion.

Over the past centuries, society has relied on clocks based on mechanical oscillators for accurate timekeeping. The operating principle is intuitive (Fig. 1a): counting the oscillations translates directly into a measure of time. For precise operation, the number of cycles made before the oscillator's energy decays (the quality factor) should be as high as possible. In pendulum clocks, the decay problem was solved by the invention of the escapement mechanism that feeds energy into the oscillator without affecting the phase of the oscillations. An equally important factor in maintaining accurate timing is the stability of the clock's frequency of oscillation. For sailors in the eighteenth century, such frequency stability was a matter of life and death, because precise timing in conjunction with the observation of celestial motion was the only way to navigate the open sea. Early sea clocks employed a simple pendulum design, but because the oscillation frequency of a pendulum depends on the local gravity and weather, this design was unsuitable for long travels, and only more stable designs made global navigation safe. Bachtold and collaborators address a similar problem of frequency stability, but in much tinier nanotube-based mechanical resonators.

The miniaturization of resonators that took place in the last few decades has expanded their use far beyond the realm of timekeeping. Compared with their larger ancestors, micro- and nanoscale resonators provide greatly enhanced sensitivity to external forces and changes in mass, and are thus excellent detectors for these quantities. However, as these lithographically defined resonators are made smaller, their Q generally degrades owing to increased dissipation by surface defects and imperfect clamping (Fig. 1b). Consequently there are ongoing efforts to increase Q using materials engineering methods such as surface treatments[2], improved crystalline purity[3] and built-in stress[4].

Recently, an alternative scheme for creating nanoscale resonators from the bottom up has emerged. One example is a mechanical 'string' resonator made out of a carbon nanotube, which is mechanically clamped at its two ends by metallic electrodes and is free to oscillate above a gate electrode (Fig. 1a). With no dangling bonds at the surface and an almost ideal clamping at the contact electrodes, carbon nanotube-based resonators were expected to reach record high quality factors. However, although early experiments demonstrated unprecedented frequency tunability[5], they reported disappointingly low Q of not more than a hundred, suggesting the presence of hidden mechanisms of dissipation.

The first breakthrough in the quest for high-Q nanotube resonators came from experiments at cryogenic temperatures[6], yielding values as high as 1.5×10^5. The low temperatures helped unravel two of the mechanisms responsible for the low

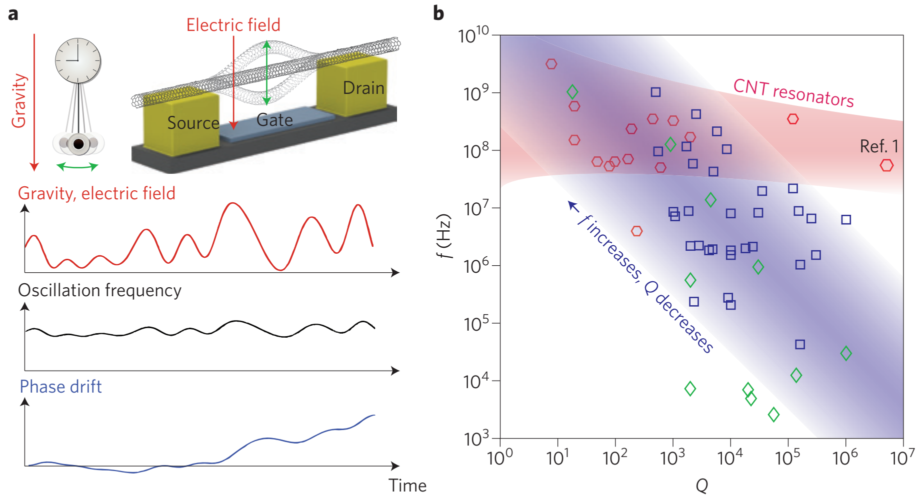

Figure 1 | Improving the quality factor of carbon nanotube mechanical resonators. **a**, The motion of a nanoscale mechanical resonator, composed of a carbon nanotube (CNT) suspended above a gate electrode, can be compared to the motion of a clock's pendulum. Just as changes in gravity will cause variations in a clock's oscillation period, electric field fluctuations (top graph) will induce fluctuations in the CNT tension and correspondingly in its resonant frequency (middle graph). In both cases, this will lead to accumulating phase drift in the time domain (bottom graph). Viewed from the frequency domain, these fluctuations manifest as broadening of the resonance peak and mask the intrinsic *Q*, despite not being associated with additional energy dissipation. **b**, The lowest resonance frequency (*f*) and the corresponding *Q* of nanomechanical resonators based on cantilevers (diamonds), beams (squares) and CNT beams (hexagons) reported in the literature[3,4,10]. While higher frequency resonators tend to have lower *Q* (shown by the purple shading), recent advances in CNT resonators suggest that in this system, extremely high *Q* can be achieved (red shading). The experiment reported by Bachtold and collaborators[1] establishes a new record for a resonator combining both high frequency and high *Q*. Image of clock, © mysondanube/iStock/Thinkstock.

Q observed in previous experiments. The first is the dissipation due to phonon–phonon scattering that occurs because of the extreme nonlinearity of the nanotube's mechanical motion, which is an effect that intensifies with increasing temperatures. The second mechanism is the dissipation of mechanical vibration energy into the motion of electrons due to the strong coupling between these two degrees of freedom. Only by suppressing the electronic motion using the phenomenon known as the Coulomb blockade did the resonators show high *Q*.

Now, Bachtold and colleagues report the next breakthrough, in which the quality factors in carbon nanotube resonators (Fig. 1a) have soared to a value of 5 million. Two key elements were essential for achieving such a high *Q*. The first is the ability to probe the resonators without any external actuation. Typically, a measurement of a mechanical resonance involves its actuation by an external drive and the monitoring of its coherent response. However, given the strong nonlinearity of nanotube resonators, even the smallest actuation hampers the achievement of high quality factors. The researchers avoided this pitfall altogether by measuring instead the oscillations produced by the thermal motion of the nanotube. Since thermal motion is stochastic, they had to probe the motional noise at the resonance frequency, and with remarkably careful measurements, they could detect thermal motion down to an effective temperature of 44 mK.

Second, the researchers realized that the limiting factor in the measurement of such high *Q* is not energy dissipation, but rather the frequency stability of the resonator. The researchers discovered that the width of the resonant peak depends on how fast they measure it — being narrower when measured faster. This signalled a possible smearing by a fluctuating environment. In analogy to the frequency drift of a sailor's pendulum clock that resulted from fluctuations in gravitation, changes in the resonance frequency of the nanotube resulted from tiny fluctuations in the electric field emanating from the gate, which randomly pulls the nanotube down and changes its tension. To alleviate this problem, Bachtold and collaborators operated the nanotube resonator in a conductance regime that was the least sensitive to the gate voltage. Still, even the tiny fluctuations in state-of-the-art voltage sources were significant enough to induce large frequency fluctuations and substantially reduce the measured *Q*. Only when batteries were used to gate the device was the resonance frequency stable enough for the resonator to unveil its intrinsic *Q* — a 30-fold improvement over the previous record[6].

The observed high values of *Q* are remarkable given the small nanotube mass, hinting at the potential for significant improvement in their already exceptional mass- and force-detection sensitivity. Large *Q* could also have a significant effect on the performance of nanotube resonators operating in the quantum limit of mechanics, allowing them to survive in their quantum state for an extended period of time. An intriguing possibility is the creation of a quantum bit based entirely on mechanical motion of the nanotube, whose logical 0 and 1 states correspond to two mechanical oscillation modes[7,8]. The ability to tailor the electron–phonon coupling in nanotubes[9] should allow to selectively couple these modes to electronic degrees of freedom and populate exactly a single phononic excitation in one of these modes. Further coherent manipulation[7,8] could then put this single phonon into a quantum superposition state between the modes. It will be exciting to see whether the low energy dissipation and long classical coherence times reported by Bachtold and collaborators will translate to similar times in their quantum analogues. If such long coherence times would be observed, this could open a new era of long-lived quantum information processing in nanotubes based entirely on mechanical motion. ❐

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