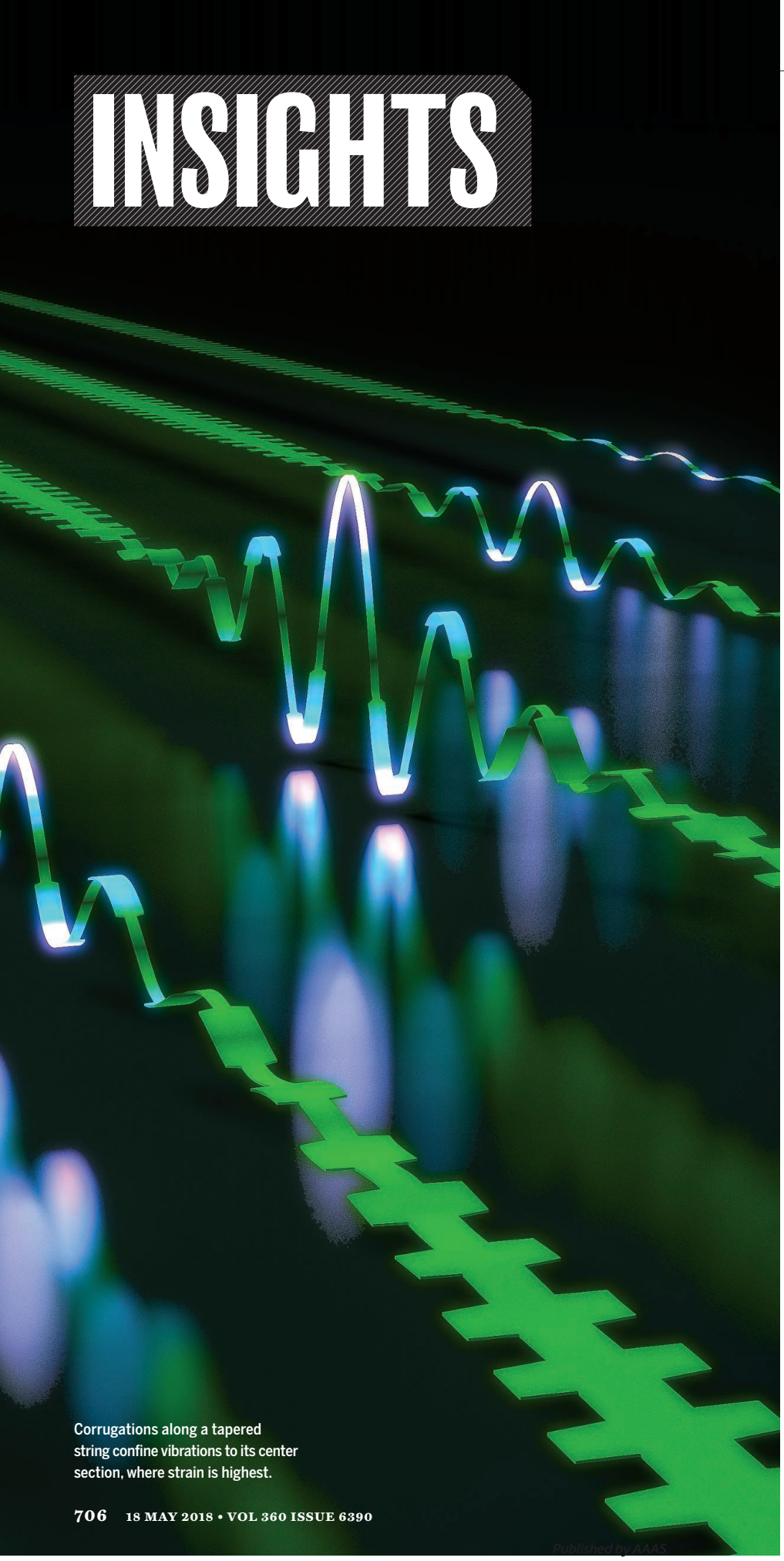
INSIGHTS



Corrugations along a tapered string confine vibrations to its center section, where strain is highest.

PERSPECTIVES

QUANTUM MATERIALS

Little is lost

Nanostrings can exploit strain engineering for unprecedented mechanical performance

By **Alexander Eichler**

Mechanical engineering is an ancient human craft, yet one that keeps emerging in ever-changing forms. Take the development of musical instruments as an example. Over the course of centuries, instrument makers mastered the selection of materials, geometrical design, and mechanical forces to generate new sounds and enable new musical styles. In recent years, physicists learned to apply similar engineering techniques to nanoscale mechanical resonators. Their efforts yielded immensely useful sensing tools, such as the atomic force microscope (*1*) and resonator devices that could play a decisive role in quantum information technology. On page 764 of this issue, Ghadimi *et al.* (*2*) demonstrate an important step in engineering the performance of such devices to an unprecedented level.

For many applications, the most important characteristic of a resonator is its quality factor Q. Roughly speaking, Q corresponds to the number of oscillations the resonator undergoes before its mechanical energy dampens out. To increase this number, one may either remove processes that cause damping or change the ratio between the energy stored in the resonator and the energy lost per oscillation cycle. Ghadimi *et al.* do both at the same time and achieve a record-high Q value of 400,000,000.

The authors build on previous work with membrane resonators by Tsaturyan *et al.* (*3*), in which a periodic pattern of holes was punched into a thin membrane, leaving only a small center island intact. The hole pattern acted as a shield that suppressed vibrations within a certain range of frequencies. Vibrations on the island interacted only very weakly with the rest of the experimental setup, almost as if they were surrounded completely by vacuum. This engineered isolation removed most of

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the damping processes and thus increased the Q of the island vibrations tremendously. Ghadimi *et al.* implemented the same approach in a string resonator through a series of corrugations.

To push Q ever further, the authors used a technique called "damping dilution" (*4*–*6*). Through the application of strain, mechanical tension is generated within the material, and the energy stored in the resonator increases. Think of a skipping rope that you tauten by pulling on both ends—the elastic material stores energy, and the rope swings faster. Importantly, the energy lost per oscillation cycle does not increase by the same amount, so it takes more cycles for the energy to dampen out than it does without the tension. This dilution process effectively increases Q.

In contrast to previous work with membranes where strain was applied uniformly, Ghadimi *et al.* realized that the effect of damping dilution can be maximized through nonuniform elastic strain engineering (*7*). They applied the highest strain exactly where it matters, namely, in the central section of the string that hosts the shielded mechanical vibrations. The collocation of the shielded vibrations and the region of highest strain is the central element of the reported success, and it is realized with a surprisingly simple geometry (see the figure).

The result reported by Ghadimi *et al.* is the latest highlight in a tradition of impressive demonstrations with mechanical devices. Functionalized micro- and nanomechanical resonators can respond to almost any physical quantity, be it magnetic, electrical, or optical. In addition, mechanical devices act as bridges between the macroscopic world and microscopic objects. For example, an atomic force microscope cantilever may be visible to the naked eye, yet it scans surfaces with (near-)atomic resolution. Researchers have been fascinated by these attributes for decades. Aided by modern fabrication methods, they developed highly sophisticated mechanical sensors to probe the nanoworld. Today, it is possible to detect nanomechanical vibrations to a precision of a fraction of an atom's size (*8*), measure the magnetic moment of an individual electron (*9*), or discern the mass of a single molecule (*10*, *11*).

It has even become possible to control mechanical devices on the fundamental quantum level, and nanomechanical resonators are envisaged as components in future quantum sensing, communication, and computation architectures (*12*, *13*). In this context, a crucial figure of merit is the so-called "Q-times-f product," where f is the mechanical resonance frequency. This term determines over how many oscillations the resonator faithfully retains quantum information. The work of Ghadimi *et al.* establishes a new record for this number as well, approaching 10^{15} Hz at room temperature. This result means that millimeter-sized mechanical resonators (comprising trillions of atoms) can be used to process single quanta of energy, a truly staggering notion.

Finally, it is interesting to view the present work in the context of "bottom-up" versus "top-down" sensors. The two terms describe opposed approaches to device fabrication. Bottom-up devices are naturally small objects like carbon nanotubes, semiconducting nanowires, nanoparticles, or graphene sheets. Such devices are grown from basic materials and have exceptionally low masses, which makes them very sensitive but also hard to manipulate. Top-down devices are patterned out of bulk material and provide much more freedom for design. However, because materials cannot be carved or etched with atomic precision, top-down devices are larger than their grown counterparts and are inherently less sensitive. To some degree, this drawback can be compensated through high Q factors and extreme aspect ratios. Indeed, Ghadimi *et al.* find that their device, a string several millimeters long, offers a force sensitivity approaching that of single carbon nanotubes, which are about 100,000 times lighter (*14*).

We are now witnessing an era of unprecedented understanding and control of nanomechanics, with a view toward many new applications. Experimental prototypes have already demonstrated the potential for revolutionary new sensors. Future nanofabrication techniques and engineering feats will hopefully enable us to bring such applications into the realm of everyday life—with mechanical devices that even the master instrument builders of past centuries would have regarded with wonder. ■

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10.1126/science.aat1983

ENERGY STORAGE

Chemical storage of renewable energy

A stable electrochemical cell selectively produces ethylene from carbon dioxide

By **Joel W. Ager**[1] *and* **Alexei A. Lapkin**[2]

The conversion of carbon dioxide (CO_2) into fuels and chemicals using renewable energy is a potential pathway to mitigate increasing CO_2 concentration in the atmosphere and acidification of the oceans (*1*). In a process that is essentially the reverse of combustion and is analogous to photosynthesis, CO_2 can be electrochemically reduced to hydrocarbons by using renewable power sources such as wind and solar (*2*). This process would not compete with direct use of renewable energy as electricity, as the objective is to store excess energy for later use. On page 783 of this issue, Dinh *et al.* (*3*) show that ethylene can be generated selectively via electrochemical CO_2 reduction at rates that could yield a technologically feasible process.

The thermodynamics of reducing CO_2 are similar to those of splitting water into hydrogen and oxygen, which has been done commercially with an energetic efficiency as high as 80% (*4*). However, CO_2 reduction is considerably more challenging because of the unreactive nature of the CO_2 molecule and the demands of controlling multiple electron and proton transfer events (12, in the case of ethylene) on the surface of the electrocatalyst. Copper catalysts bind carbon monoxide (CO) and other reaction intermediates in such a way as to produce two-carbon products such as ethylene and ethanol (*5*). However, it has been difficult to steer the reaction toward any one product. Moreover, most experimental studies provide CO_2 to the electrode from aqueous solution, where its finite

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