

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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ENERGY STORAGE

Chemical storage of renewable energy

A stable electrochemical cell selectively produces ethylene from carbon dioxide

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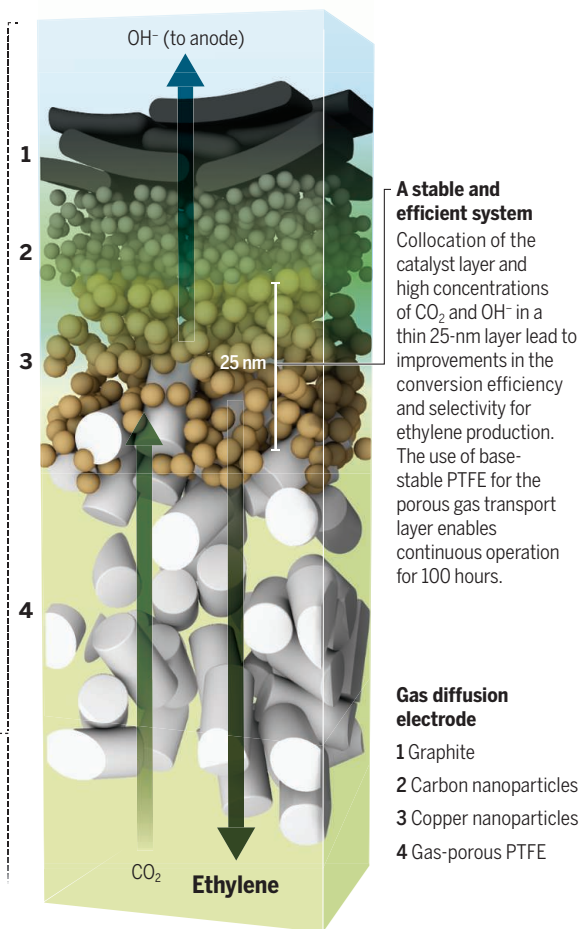
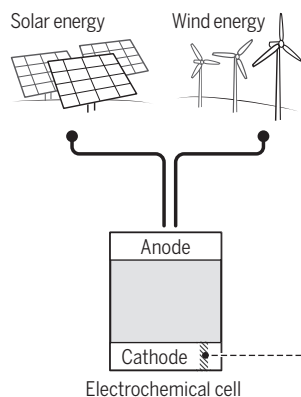
The conversion of carbon dioxide (CO₂) into fuels and chemicals using renewable energy is a potential pathway to mitigate increasing CO₂ concentration in the atmosphere and acidification of the oceans (1). In a process that is essentially the reverse of combustion and is analogous to photosynthesis, CO₂ 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 CO₂ reduction at rates that could yield a technologically feasible process.

The thermodynamics of reducing CO₂ 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, CO₂ reduction is considerably more challenging because of the unreactive nature of the CO₂ 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 CO₂ to the electrode from aqueous solution, where its finite

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Efficient conversion

Dinh *et al.* show that the use of very thin copper-catalyst layers in a gas diffusion electrode leads to efficient and selective electrochemical conversion of CO₂ to ethylene. Such a process could help to mitigate rising atmospheric CO₂ concentrations if the energy required for the conversion comes from renewable sources.



solubility leads to an upper, diffusion-limited current density of a few tens of milliamperes per square centimeter—far below what would be commercially relevant.

A breakthrough in efficiency can be achieved through intensification of mass transfer within the process. Process intensification is a chemical engineering approach that can achieve manyfold increases in product throughput by eliminating mass and energy transport limitations and exploiting potential synergies, such as combining multiple functions (for example, reaction and separation) (6). Use of a gas diffusion electrode similar to those in fuel cells can greatly reduce the mass-transfer constraint for CO₂ and has enabled current densities above 500 mA/cm² for formation of one-carbon products such as CO (7). However, careful management of the gas phase CO₂, liquid electrolyte, and solid electrocatalyst is required to maintain selectivity and minimize parasitic reactions such as water reduction.

Higher pH conditions can increase the yield of two-carbon products (8), but CO₂ itself is acidic, setting an upper limit to the pH attainable in a conventional experiment. Dinh *et al.* show that very high hydroxide (OH⁻) concentrations can be maintained at the catalyst surface, provided that the elec-

trochemical conversion is faster than the homogeneous reaction of CO₂ with OH⁻ to form bicarbonate. An optimal balance between these competing processes is attained through the use of very thin (~25 nm) Cu-catalyst layers deposited on the gas diffusion electrode (see the figure). The collocation of the electrocatalyst and high CO₂ and OH⁻ concentrations led to about 70% current efficiency to ethylene at current densities up to 750 mA/cm². When the authors used thicker catalyst layers (for example, 100 nm), a region of lower OH⁻ concentration formed, resulting in lower selectivity for ethylene.

To be economically viable, the process would need to operate continuously. Dinh *et al.* found that the highly basic conditions required to enhance ethylene yield led to deterioration of the carbon-based electrode material within an hour. As an alternative, they designed and implemented a gas diffusion electrode consisting of base-stable polytetrafluoroethylene (PTFE), with copper nanoparticles as the catalyst and carbon nanoparticles and graphite providing electrical contact. Use of this electrode led to a lower current density (~300 mA/cm²), but it was stable for 100 hours.

A full electrochemical CO₂-reduction system must also oxidize water to oxygen at the

anode for sustained operation. Dinh *et al.* performed such a full-cell experiment, using a nickel iron oxide (NiFeO_x) to catalyze the oxygen-evolution reaction at the anode. They measured a full-cell energy conversion efficiency, which captures all losses (overpotentials at the cathode and anode and electrical resistance of the electrolyte), of 34%. This value is lower than the 60 to 80% achieved for water splitting but is comparable to CO₂-reduction cells, which make one-carbon products such as CO or formate and have lower cathode overpotentials (9).

Although the work of Dinh *et al.* is an important step toward chemical storage of renewable energy, challenges remain. Their reactor, and indeed nearly all CO₂-reduction reactors in the literature, makes products which are either entrained in the CO₂ stream or dissolved in the electrolyte, leaving product separation as an unsolved challenge (10).

There is a lively discussion in the literature regarding the prospective economics of electrochemical CO₂ reduction (11). Although there is consensus that a carbon tax would be required to provide an incentive for CO₂ conversion, opinions diverge on the economic viability of the conversion targets (such as CO and/or syngas, ethylene, and ethanol). Benchmark demonstrations such as that of Dinh *et al.* can be used to focus the discussion.

The products of electrochemical CO₂ reduction are simpler than those of natural photosynthesis, yet they are the most ambitious targets of preparative electrochemical chemistry; most work over the past 100 years or more has focused on simpler transformations involving far fewer electron transfers (12). Demonstrations such as that of Dinh *et al.*, combined with increasing understanding of the mechanism, could lead to a commercially viable electrochemical CO₂-reduction process for mitigating rising atmospheric CO₂ concentrations and promoting the use of renewable energy. ■

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