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earlier have higher inferred $^{26}\text{Al}/^{27}\text{Al}$ ratios.

Coki is 5 μm in diameter and is primarily composed of the feldspar mineral anorthite, whose Al/Mg ratio is high enough for ^{26}Al to be detected if present at the same level as seen in many meteoritic CAIs, despite its small size. However, the authors found no evidence for extinct ^{26}Al in this grain, and their upper limit on the initial $^{26}\text{Al}/^{27}\text{Al}$ ratio indicates that it must have formed at least 1.7 million years after the oldest CAIs. Thus, large-scale transport of material from the inner to the outer solar nebula must have taken place over a time scale of millions of years, and Wild 2 itself must have accreted after this time. This observation supports the conclusion that comets are not simply collections of interstellar or early-formed primitive materials.

A very different type of material was studied by Duprat *et al.* The AMMs in their study were collected by melting and filtering snow that fell in the mid-20th century near the French-Italian CONCORDIA station (see the figure, panel B). Among the recovered particles were some fluffy, fine-grained ones with much higher carbon contents than seen in other primitive materials, including meteorites, most IDPs, and Wild 2 samples. Detailed study of these “ultracarbonaceous” AMMs (UCAMMs) revealed that the carbon is in the form of a poorly ordered organic material, similar to that seen in the most

primitive meteorites and IDPs. Most interesting is the discovery that the organic matter is highly enriched in deuterium, with D/H ratios up to 30 times terrestrial values. Such high D/H ratios have been seen in carbonaceous chondrite meteorites (12) and IDPs (13), but typically only as submicrometer-to micrometer-sized grains (“hot spots”). In contrast, organics in the UCAMMs show extreme D/H ratios extending over tens of square micrometers. The origin of D enrichments in primitive organic matter is a matter of controversy, with interstellar, protostellar, and parent-body processes all possibly playing a role.

Embedded in the D-rich organic matter were crystalline and amorphous minerals similar to those found in IDPs and Wild 2 samples. The primitive nature of the UCAMMs, especially the high abundance of D-rich organic matter, suggests a connection to icy bodies in the outer solar system, with comets being the most likely to supply dust to Earth-crossing orbits. The 1986 Giotto mission to comet Halley identified large numbers of carbon-rich particles intermixed with silicate minerals [so-called CHON particles (14)], and the UCAMMs may well be similar objects. However, similar extremely D-rich carbonaceous materials have not yet been identified in the only unambiguously cometary samples, those from Wild 2 (15). This may be due in part to

sampling biases, but likely also reflects substantial chemical diversity among comets.

Detailed laboratory comparisons of materials from diverse parent bodies from throughout the protosolar disk can provide insights into processes including the timing of grain formation and transport, as well as the origin and distribution of organic matter. Moreover, the very high carbon contents of UCAMMs may well have profound implications for the original delivery of organic molecules to the early Earth, with possible consequences for the earliest prebiotic chemistry.

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ENGINEERING

The Impact of Tellurium Supply on Cadmium Telluride Photovoltaics

Ken Zweibel

For decades, the material associated with photovoltaic (PV) cells has been silicon. However, after many years of development, cadmium telluride (CdTe) PV modules have become the lowest-cost producer of solar electricity, despite working at lower efficiency than crystalline silicon cells. CdTe sales are growing rapidly, but there is concern about projecting hundredfold increases in power production relative to current production with CdTe PV modules. One reason is that Te, a humble nonmetal that is actually abundant in the universe, is as rare as many of the precious metals recovered from Earth’s crust (1). Fur-

thermore, current technology now uses Te at rates that are substantial fractions of its supply. Here, I argue that the long-term potential for CdTe PV modules need not be bleak, given realistic developments in module technology and Te recovery.

That Te supply is even an issue in thinking about the future of renewable energy results from recent decreases in production costs of the PV module—the deployable device, or large-area aggregation of solar cells, that contains the active PV materials and delivers current. CdTe module production costs have dropped from over \$2/W in 2004 to \$0.84/W in 2010, the lowest in photovoltaics (2). A key advantage of CdTe for thin-film devices is that it can be deposited rapidly. For other thin-

Better optical designs and enhanced recovery of tellurium may boost the potential for large-scale energy production from thin-film cadmium telluride solar cells.

film PV materials, the vapor-phase composition must be carefully adjusted and controlled, which slows the process and adds to costs. CdTe can be deposited at rates of micrometers per minute over large substrates, versus nanometers per minute for amorphous silicon.

These cost reductions bring PV closer to competitiveness with current power generation cost. In the United States, the approximate cost would be as low as 15 cents per kilowatt-hour (c/kWh) for parts of the Southwest that have the most available sunlight. For the rest of the USA, it would be 20 c/kWh (retail prices for electricity in the USA are now about 10 c/kWh) (3, 4).

Any favorable projections for CdTe PV will be moot if its contribution to power pro-

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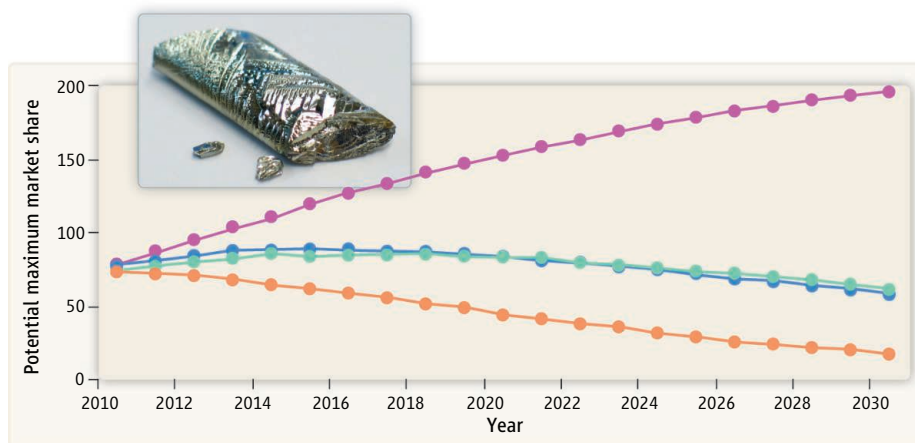
duction is severely limited by Te supply. For the present technology, generating 1 gigawatt (GW) of power requires 91,000 kg (91 metric tons, MT) of Te (a cost of about \$20 million). If all of the PV delivered in 2009–7 GW—had been produced with CdTe, about 640 MT of Te would have been required, which is comparable to its present annual production (5, 6).

If PV is to supply 10% of the projected demand of electricity worldwide in 2030, the per annum growth rate must be 18.5%; for 25% of world electricity, it must be 25%. In 2030, the annual production would require 200 GW/year (at 10% electricity supply) or 670 GW/year (at 25% supply). For the current CdTe modules, 19,000 or 61250 MT of Te per year, respectively, would be needed, equivalent to an increase in supply by a factor of about 40 to more than 100, respectively.

However, future developments may make this challenge less daunting. First, there will likely be some gains made in supply given the inducement of higher Te prices. The crustal abundance of Te is similar (7) to that of platinum, but the actual recovery of Te is more than twice that of platinum. The existing supply is obtained almost exclusively through Te recovery as a by-product of refining copper. Ojebuoboh (8) has described how the supply could expand from 500 to 1500 MT/year by electrorefining more copper to recover more Te. Availability should also increase simply through the historical increase in copper extraction, typically 1 to 3% per year. Also, several other primary metals besides copper have Te impurities. The highest Te concentrations occur in gold deposits, and Te could be refined from zinc and lead (9).

Further, there are already sources of Te as a primary ore. Mines in Mexico (10), China (11), and Sweden (12) have rich bismuth telluride ores, with Te concentrations of almost 20% (9). The challenge with primary ores is that few have been identified, and that the Te must be rich enough to refine alone. This is perhaps about 0.25% concentration, if no by-product minerals can be processed and sold. Finally, there appear to be undersea deposits (7); Te-rich layers (mean concentration of 50 parts per million) coat undersea ferromanganese crusts.

Most importantly, it may also be possible to use much less Te and still maintain module performance. One possibility is to decrease the thickness of the active layer. It does not take 3 μm of CdTe to absorb the solar spectrum. In fact, over much of its absorption range, the CdTe light absorption coefficient is above $10^5/\text{cm}$, that is, it absorbs 63% of available photons in 10^{-5} cm, or 0.1 μm (a



Projecting paths for CdTe photovoltaics. The concerns about Te availability limiting CdTe PV module production assume that the layer thickness will be maintained at 3 μm . Projections of maximum market share attainable are shown based on modest increases in Te production (from 1% growth per year in copper production, its main supply route) and module efficiency (15%), but substantial decreases in CdTe active-layer thickness. The blue and purple lines are market-share maxima if 10% of the world electricity is made from PV in 2030, with layer thicknesses of 0.67 and 0.2 μm , respectively. Similar projections (orange and green) are for 25% world electricity production by PV in 2030. In all cases, with thin enough CdTe, nearly 100% market share might be attained. The inset shows tellurium in its native form.

thickness decrease of a factor of 30).

However, it is not so simple to make such ultrathin CdTe films work well. Two major loss mechanisms for absorbed photons have to be addressed to use CdTe at 0.1- μm thickness. First, 37% of the spectrum would be lost, and the equivalent loss of efficiency would be unacceptable. Second, absorption rises to 10^{-5} cm for higher-energy (shorter-wavelength) light, but longer-wavelength light just above the 1.5-eV band gap of CdTe (the minimum light energy at which it generates a photocurrent) requires thicker CdTe in order to be absorbed. Because 1.5 eV is the

the 0.1- to 0.3- μm range. The mirror material is a combination of a transparent conductive oxide (ZnO) and a silver or aluminum film on top of the back contact.

The rapid deposition of thicker CdTe layers help to minimize manufacturing costs, which presently are greater than costs associated with Te. When Te becomes the limiting cost factor, a shift to thinner CdTe will likely require slower deposition rates to gain greater control of layer thickness.

The other major lever in reducing the amount of Te needed is to increase efficiency. CdTe modules are 11% efficient, and the best cells are 16.5%. Theoretical efficiencies for a single junction cell top out at 33%, and the band gap for CdTe is very close to the optimum for taking advantage of the solar spectrum. Conservative long-term goals for the efficiency of CdTe modules tend to be about 15%. The table shows how the amount of Te required per gigawatt of energy generation would change for different efficiencies and layer thicknesses.

What does this mean in terms of the long-term contribution of CdTe to PV energy production? The growth of PV deployment will take decades. During that time, Te refining, Cu extraction, CdTe module efficiency, and CdTe layer thickness can be improved. The projections shown in the figure have not counted on more Te from new bismuth telluride ores, undersea ridges, or greater refining of non-Cu ores (13). The limit on market share for 10 and 25% production of the world's electricity by PV shown in the figure are for a CdTe module efficiency of 15%. For 10% PV electricity production in 2030, the

POTENTIAL FOR USING LESS TE (IN METRIC TONS) PER GIGAWATT OF PHOTOVOLTAIC OUTPUT			
Efficiency	CdTe layer film thickness		
	3 μm (now)	2/3 μm	0.2 μm
10%	100 MT/GW	22 MT/GW	6.6 MT/GW
15%	67 MT/GW	15 MT/GW	4.4 MT/GW

middle of the solar visible range, too much light would be wasted.

Two commercial PV technologies already deal with these problems—amorphous and thin-film microcrystalline silicon. They use two strategies to trap light inside the cell. One is to deposit a mirror on the back of the cell, just above the metal back contact. The other is to texture the top, transparent conductive oxide contact so that light is bent as it enters the cell (making the first pass longer, and leading to total internal reflection if combined with a back-side mirror). Amorphous silicon, with about the same absorption coefficient as CdTe, is already made with these ancillary components, and layers are in

numbers are encouraging for 0.67- μm layer thickness, and of course better for 0.2 μm . In this case, all modules could be CdTe. For the 25% PV electricity in 2030, the goal could be reached with 0.2- μm layers.

So this analysis brings us back to the question—will CdTe contribute substantially to renewable energy production? Supply and demand will almost certainly remain a key issue in CdTe PV production. However, projections that underestimate CdTe PV at this early stage of development assume a situation for Te supply and use that will be nearly static during the next 20 years. In an area driven by innovation, this grim scenario seems unlikely.

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NEUROSCIENCE

Epigenetics and Cognitive Aging

J. David Sweatt

Cognitive decline, especially in memory capacity, is a normal part of aging (1). Indeed, the painful reality is that aging-related cognitive decline likely begins when one is in their late 40s. This deterioration is particularly pronounced in declarative memory—the ability to recall facts and experiences—and has been associated with aberrant changes in gene expression in the brain's hippocampus and frontal lobe. However, the molecular mechanisms underlying these changes in gene regulation are not currently known (2, 3). On page 753 of this issue, Peleg *et al.* (4) bolster an emerging hypothesis that changes in the epigenetic modification of chromatin in the adult central nervous system drive cognitive decline.

Chromatin remodeling in the hippocampus is necessary for stabilizing long-term memories (5–8). The relevant molecular mechanisms include DNA methylation and the modification of histone proteins by acetylation, phosphorylation, and methylation. These epigenetic changes involve covalent chemical modifications by enzymes such as histone acetyltransferases and histone deacetylases. Whether alterations in these mechanisms contribute to age-related changes in gene transcription and memory decline are unknown (8).

Peleg *et al.* found that aged mice exhibit a disruption of memory-associated activity-

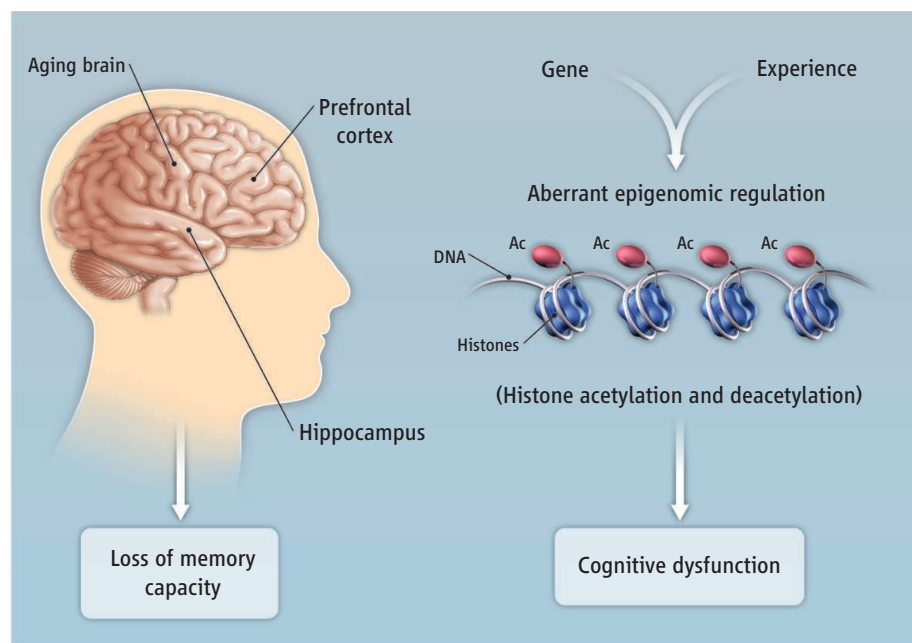
and experience-dependent epigenetic modification at the histone H4 lysine 12 (H4K12) acetylation site. This correlated with the loss of almost all normal memory-associated transcription in the hippocampus. Moreover, the authors identified a memory-associated gene, Formin 2 (an actin regulatory protein), and showed that its function is necessary for normal memory, and that its transcriptional regulation is disrupted in aging.

In a final series of studies with poten-

Changes in the epigenetic modification of chromatin may be the molecular basis for memory decline in aging adults.

tial clinical relevance, Peleg *et al.* show that intrahippocampal infusion of mice with suberoylanilide hydroxamic acid, an inhibitor of histone deacetylase, increased memory-associated H4K12 acetylation in the central nervous system, restored memory-associated transcriptional regulation, and improved behavioral memory function in aged animals.

The study presents a major advance in thinking about the role of histone modifi-



Aging and memory. Experience-epigenome interactions may drive memory formation. Decline in this system is a hypothetical basis for cognitive aging.