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Dynamic Flake Expansion: Carbon-Intercalation Wedging to Expose Buried Metal Surface Under Bias

Dynamic flake expansion is a secondary inventive step of the Hydrogen-Aluminum Energy Cell disclosed in U.S. Provisional Application No. 64/055,649, covering both carbon-intercalation wedging that exposes buried metal-flake surface under bias and the hydrogen-locked expanded state that holds that surface open for positive-feedback capacity gain. A surface-bond storage cell stores energy as hydrogen bonded to exposed metal-flake surface, so its capacity is bounded by how much flake surface the gel can reach. A flake at rest sits folded, stacked, or otherwise compact, with much of its surface buried and unavailable. The disclosed mechanism, dynamic flake expansion, addresses this by driving mobile carbon species from the gel between the flake layers under applied bias, where they act as wedging species that separate the layers without rupturing the metal lattice. The separation exposes previously buried surface area to the gel, the newly exposed surface binds hydrogen, and the bonded hydrogen lowers the surface energy of the expanded configuration enough to hold the flake open. Capacity becomes bounded not by the resting surface but by the fully expanded surface.

The Buried-Surface Problem

The disclosed cell stores energy as hydrogen bonded to the surface of metal nanoflakes suspended in a proton-conducting carbon gel. Hydrogen chemisorption on metal surfaces such as aluminum is well-characterized surface chemistry; what is new is the cell architecture built around it, and the present mechanism is one element of that architecture. In a surface-bond chemistry, the quantity of energy a flake can hold scales with the amount of flake surface the gel can actually reach. The difficulty is that a flake at rest does not present all of its surface. In its contracted resting state, the flake exists as a folded, stacked, or otherwise compact structure with a defined low surface area, and a portion of its surface is buried inside the folded or stacked geometry where the gel and its protons cannot access it. A storage architecture that relied only on the resting surface would be capped at that low number. The mechanism described here lifts that cap by reversibly opening the flake during charge.

Reversible Morphological Transformation

The flake undergoes a reversible morphological transformation between two states. In the contracted resting state it is folded, stacked, or otherwise compact, with low surface area. In the expanded charged state it is unfolded, separated, or otherwise extended, with substantially higher surface area. The transformation is driven by applied charging bias, locked by a bonded hydrogen population at the expanded surfaces, and reversed by discharge. The transformation is between morphological configurations of the same flake; it is not a dissolution and reprecipitation of the metal, and it does not rupture the metal lattice.

Carbon Intercalation as the Wedging Species

Carbon intercalation into metallic lattices, and electrochemically driven exfoliation and morphological restructuring of stacked metal nanoparticles under applied bias, are established phenomena characterized in the surface-science, intercalation-chemistry,

and 2D-materials literature. The novelty here is not the discovery of intercalation but the architecture that recruits it as the wedging mechanism of a reversible storage cell. The transformation is mediated by carbon species from the gel intercalating into the flake structure under applied bias. The carbon migrates from the auxiliary carbon reservoir, and from the adjacent gel framework where mobile carbon is liberated by the local field, to the flake surface, then between the flake layers, then into the inter-layer gallery, where it acts as a wedging species. The wedging admits separation of the flake layers without rupture of the metal lattice, exposing previously buried surface area to the gel. The carbon is therefore not consumed as a faradaic reactant in this step: it is inserted mechanically to hold the layers apart, and it is the geometric act of insertion that exposes new surface.

Where the Carbon Inserts: Coordination Asymmetry

The carbon does not insert uniformly. Atoms within a flake occupy distinct coordination environments depending on their position in the branching structure: atoms at branch endpoints occupy loose 3-coordinate environments, atoms at branch junctions occupy tight 4-coordinate environments, and atoms within branch trunks occupy intermediate coordinations. Carbon intercalation occurs preferentially at the boundaries between 3-coordinate and 4-coordinate regions, where the local coordination imbalance admits insertion of carbon species and the resulting redistribution of metal-metal coordinations.

At such a boundary, the insertion event admits one or more coordination redistribution patterns. A 4-coordinate cluster with four nearest neighbors splits into two 2-coordinate pairs upon carbon insertion at the central bond, and the splitting exposes the previously buried internal surface. A 3-coordinate cluster with three nearest neighbors splits into a 1-coordinate atom and a 2-coordinate pair upon carbon insertion, again exposing buried internal surface. Higher-order redistributions at

junction points of higher coordination are also admitted. Each redistribution event exposes new metal surface area to the gel and presents new hydrogen-binding sites at that exposed surface.

Hydrogen Locks the Expanded State

Wedging alone does not hold the flake open. That adsorbed hydrogen lowers the surface energy of a metal surface is well-established surface chemistry; the invention's contribution is configuring that known effect as the latch that stabilizes the expanded morphology. The expanded state is energetically favored over the contracted state only when bonded hydrogen is present at the newly exposed surfaces. Bonded hydrogen lowers the surface energy of the expanded configuration to a value below the surface energy of the contracted configuration, and that inversion of relative stability is what locks the flake open during the charged condition. Without bonded hydrogen, the flake would prefer the contracted state and would re-fold spontaneously.

This produces a positive-feedback storage architecture: more bonded hydrogen exposes more surface area, which admits more bonded hydrogen, which exposes still more surface area, up to a saturation set by the fully expanded flake morphology. Capacity is not capped by the initial surface area; it is capped by the fully expanded surface area, which the disclosure states may be a multiple of the contracted surface area, typically 2 to 5 times, with stretch values up to 8 to 10 times.

Capacity Augmentation from Two Contributions

The capacity augmentation from dynamic expansion derives from two complementary contributions, each of which rests on known physical behavior put to a new architectural purpose. The first is lattice expansion of the metal framework upon carbon intercalation, a routine consequence of intercalation into a host lattice, here contributing approximately 5 to 12 percent additional accessible surface area. The second is fractal branch separation at the coordination asymmetry boundaries,

contributing additional accessible surface area through exposure of previously buried inter-branch surface, with this contribution scaling with the fractal generation count of the flake morphology. Fractal branch separation is the dominant contributor: higher generation counts present more coordination asymmetry boundaries available for intercalation, and each additional generation level adds incrementally to the accessible surface.

The two contributions combine multiplicatively. The disclosure gives total dynamic-expansion factors of approximately 1.30 to 1.55 times the static-flake capacity for basic three-level fractal flakes, approximately 1.50 to 2.00 times for moderate-generation-count flakes of 8 to 16 levels, and approximately 1.80 to 3.00 times for high-generation-count flakes of 16 to 32 levels, with stretch values up to approximately 4.00 times in maximum-generation-count embodiments at the practical limits of synthesis.

Reversal Upon Discharge

The expanded state reverses to the contracted state upon discharge. As bonded hydrogen is released through the cold-proton egress path, the surface-energy stabilization of the expanded state is removed; at the same time, the intercalated carbon de-intercalates back into the gel as the field driving its intercalation is removed. These two coupled processes return the flake to its contracted resting state, ready for the next charging cycle. Because the layers were separated rather than the lattice broken, and because the carbon leaves as the field is removed, the cycle is reversible.

The morphological work of intercalation, de-intercalation, unfolding, and re-folding introduces a hysteresis between the charging voltage and the discharging voltage, in the range of approximately 0.1 to 0.5 volts at typical operating rates, corresponding to a round-trip energy efficiency in the range of approximately 70 to 90 percent. The disclosure characterizes this efficiency as acceptable for stationary, automotive, and grid-scale applications and offset by the gains in energy density and cycle life.

Disclosure Scope

This article describes the dynamic flake expansion mechanism, carbon-intercalation wedging to expose buried metal surface under bias, as disclosed in U.S. Provisional Application No. 64/055,649. It reflects an early-stage provisional disclosure of concepts and mechanisms. The mechanisms, ranges, and outcomes stated here are those recited in that application; values appearing as approximate ranges or as projected, estimated, or stretch figures are presented as such in the application and are not measured guarantees. Nothing here should be read as a claim of reduction to practice beyond what the application itself states.

Hydrogen-Aluminum Energy Cell (/h-al-battery)

All 40 steps → (/inventive-steps)

Sealed electrochemical cell storing energy as reversible covalent hydrogen bonds on carbon electrodes.

Provisional application

PRIMARY TECHNICAL DISCLOSURE

- A Hydrogen-Aluminum Surface-Bond Storage Cell with Bulk-Equipotential Charge Retention (/articles/a-hydrogen-aluminum-surface-bond-storage-cell-with-bulk-equipotential-charge-retention)

SECONDARY TECHNICAL

- Charge Retention by Bulk-Equipotential Saturation Without an Internal Separator (/articles/h-al-battery/bulk-equipotential-charge-retention)
- Storing Energy as Electron-Stabilized Metal-Hydrogen Surface Bonds Formed by Proton-Coupled Electron Transfer (/articles/h-al-battery/hydrogen-metal-surface-bond-storage)
- Electron-Mediated Bond Stability: The Kinetically Trapped Idle State Behind Indefinite Calendar Life (/articles/h-al-battery/electron-mediated-bond-stability)
- Hot-Proton Charging Versus Cold-Proton Discharge: The Bias-Gated Asymmetry That Blocks Self-Charge and Self-Discharge (/articles/h-al-battery/hot-cold-proton-asymmetry)

- Asymmetric Dual-Domain Proton Paths: Separate Ingress and Egress Routes in a Hydrogen-Aluminum Storage Gel (/articles/h-al-battery/asymmetric-dual-domain-paths)
- Hydrophobic Gating: Rejecting Neutral and Molecular Hydrogen While Admitting Only Biased Protons (/articles/h-al-battery/hydrophobic-gating)
- The Storage Gel as a Polarized Electrochemical Switch: Coherent Alignment, Equipotential Locking, and Load-Proportional Discharge (/articles/h-al-battery/gel-polarized-switch)
- Flake-Flake Electrostatic Isolation: DLVO Repulsion as a Self-Discharge Barrier in a Separator-Free Hydrogen-Aluminum Cell (/articles/h-al-battery/flake-electrostatic-isolation)
- **Dynamic Flake Expansion: Carbon-Intercalation Wedging to Expose Buried Metal Surface Under Bias (/articles/h-al-battery/dynamic-flake-expansion)**
- Hydrogen-Locked Expanded State: Surface-Energy Inversion as a Positive-Feedback Capacity Mechanism (/articles/h-al-battery/hydrogen-locked-expanded-state)
- Secondary Carbon-Hydrogen Storage on Transmuted Intercalated Carbon (/articles/h-al-battery/secondary-carbon-hydrogen-storage)
- Mechanochemical Strain Self-Healing and Use-Positive Aging in a Bulk-Equipotential Hydrogen-Aluminum Cell (/articles/h-al-battery/mechanochemical-self-healing)
- Boron Doping of the Carbon Framework as a Multi-Function Precision Multiplier (/articles/h-al-battery/boron-doping-precision-multiplier)
- The Floating Aluminum Equipotential Extension Layer: A Multifunctional Inner Case for the Bulk-Equipotential Cell (/articles/h-al-battery/aluminum-equipotential-extension-layer)

Hydrogen-Aluminum Energy Cell overview → (/h-al-battery)