

# Hydrogen-Locked Expanded State: Surface-Energy Inversion as a Positive-Feedback Capacity Mechanism

This article documents the hydrogen-locked expanded state, a secondary inventive step of the Hydrogen-Aluminum Energy Cell disclosed in U.S. Provisional Application No. 64/055,649, together with the dynamic flake expansion via carbon-intercalation wedging that makes that locking possible. A metal nanoflake that stores hydrogen at its surface faces a structural problem: a folded, stacked, or otherwise compact flake exposes only a small, fixed surface area, so its storage capacity is capped by whatever area existed before charging. The disclosed mechanism resolves this by making the act of storing hydrogen itself enlarge the available surface. Bonded hydrogen at newly exposed flake surfaces lowers the surface energy of the expanded configuration below that of the contracted configuration, inverting their relative stability and locking the flake open during the charged condition. Because more bonded hydrogen exposes more surface area, which admits still more bonded hydrogen, the architecture operates as positive feedback whose capacity is set not by the initial surface area but by the fully expanded flake morphology.

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## **The Fixed-Surface-Area Problem**

In the disclosed cell, hydrogen storage capacity at the flake surface is set by the surface atom density of the metal, the fraction of surface atoms participating in hydrogen binding, and the total flake surface area per unit flake mass. A metal nanoflake in its resting condition exists as a folded, stacked, or otherwise compact structure with a defined low surface area. If the flake stayed in that compact condition, its storage would be bounded by the area present before any charge was applied, and much of the flake's mass would remain buried and inaccessible to hydrogen binding. The mechanism described here addresses that limit by transforming the flake during charging so that previously buried area becomes available, and then holding that expanded condition in place for the duration of the charged state.

## **Reversible Morphological Transformation**

The metal nanoflakes undergo a reversible morphological transformation between a contracted resting state and an expanded charged state. In the contracted state, the flake is folded, stacked, or otherwise compact, with a defined low surface area. In the expanded state, the flake is unfolded, separated, or otherwise extended, with substantially higher surface area. The transformation is driven by applied charging bias, locked by bonded hydrogen population at the expanded surfaces, and reversed by discharge. These three roles, drive, lock, and reverse, are distinct: the bias initiates the change, hydrogen sustains it, and discharge undoes it. The locking role is the subject of this article.

## **Carbon Intercalation as the Wedging Species**

Carbon intercalation into metallic lattices, the formation of metal-carbon adsorption complexes at metal surfaces, and electrochemically driven exfoliation of layered or stacked metal nanoparticles under applied bias are all established in the surface-science, intercalation-chemistry, and battery-materials literature. The disclosed cell

does not claim those effects as new. What is specific to the cell is the role assigned to carbon intercalation within its architecture: the morphological transformation is mediated by carbon species from the gel intercalating into the flake structure under applied bias. 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 flake layers, then into the inter-layer gallery as wedging species. This wedging admits separation of the flake layers without rupture of the metal lattice, exposing previously buried surface area to the gel. The carbon does the mechanical work of prying the layers apart and exposing new area; what keeps that newly exposed area from re-folding is a separate, energetic effect supplied by hydrogen. The novelty is not the wedging itself but its integration with hydrogen locking into a single governed storage mechanism.

## **Surface-Energy Inversion**

That an adsorbed species can lower the surface energy of a metal surface, and thereby shift which configuration of a nanostructure is energetically preferred, is a well-established result of surface science and is not claimed as new here. The disclosed cell applies that known effect in a specific structural role: the expanded state is energetically favored over the contracted state only when bonded hydrogen is present at the newly exposed flake surfaces. Bonded hydrogen lowers the surface energy of the expanded configuration to a value below the surface energy of the contracted configuration. That inversion of relative stability is what locks the flake in the expanded state during the charged condition. Without bonded hydrogen, the flake would prefer the contracted state and would re-fold spontaneously. The novelty is the architecture that puts a known surface-energy effect to work as a structural latch: the same hydrogen that constitutes the stored energy also pays the energetic cost of keeping the flake open, so the storage species and the structural latch are one and the same, and the open configuration is stable precisely when, and because, it is loaded with hydrogen.

## **The Positive-Feedback Loop**

Because the latch is supplied by the stored species, the locking mechanism is a positive-feedback storage architecture. More bonded hydrogen exposes more surface area, which admits more bonded hydrogen, which exposes still more surface area. Each increment of hydrogen both adds to the stored charge and stabilizes a larger open configuration, which in turn presents more sites for the next increment. The loop is self-reinforcing rather than self-limiting in its early progression, which is what allows the flake to be driven well past its resting surface area during a single charge.

## **Capacity Capped at Full Expansion**

The positive feedback does not run away without bound. It proceeds up to a saturation set by the fully expanded flake morphology. Capacity is therefore not capped by the initial surface area; it is capped by the fully expanded surface area, which may be a multiple of the contracted surface area, typically 2 to 5 times, with stretch values up to 8 to 10 times in the disclosed embodiments. Once the flake reaches its fully expanded morphology, there is no further area to expose and the loop terminates at that ceiling. The capacity cap is thus a structural property of the flake at full extension rather than a property of its resting shape.

## **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; simultaneously, intercalated carbon deintercalates 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. The reversal is the mirror of the charge: removing hydrogen removes the energetic basis for the inversion, so the flake again prefers, and returns to, its compact form.

## Relationship to Overall Capacity Augmentation

The capacity augmentation provided by dynamic expansion derives from two complementary contributions: lattice expansion of the metal framework upon carbon intercalation, and fractal branch separation at coordination asymmetry boundaries that exposes previously buried inter-branch surface. These contributions combine multiplicatively, with disclosed total dynamic-expansion factors ranging from 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, and approximately 1.80 to 3.00 times for high-generation-count flakes, with stretch values up to approximately 4.00 times in maximum-generation-count embodiments. The hydrogen-locking mechanism is what makes these expanded configurations persist long enough to be charged: without the surface-energy inversion holding the flake open, the exposed area gained by intercalation and branch separation would not be available for storage.

## Disclosure Scope

This article describes a mechanism disclosed in U.S. Provisional Application No. 64/055,649. The provisional is an early-stage disclosure of concepts and mechanisms. The numerical ranges stated above, including expansion multiples, dynamic-expansion factors, and surface-fraction and capacity figures, are those recited in the specification and are presented as disclosed ranges, not as measured results. No mechanism, primitive, threshold, or outcome stated here is asserted beyond what the specification discloses.

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 \(/articles/h-al-battery/aluminum-equipotential-extension-layer\)](#)

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[Hydrogen-Aluminum Energy Cell overview → \(/h-al-battery\).](#)