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Asymmetric Dual-Domain Proton Paths: Separate Ingress and Egress Routes in a Hydrogen-Aluminum Storage Gel

This article documents asymmetric dual-domain ingress and egress paths, a secondary inventive step of the Hydrogen-Aluminum Energy Cell disclosed in U.S. Provisional Application No. 64/055,649, together with the hot-proton charging versus cold-proton discharge asymmetry and the hydrophobic gating rejection of neutral and molecular hydrogen that make those paths selective. A surface-bond energy storage cell faces a structural tension: the same hydrogen that must be driven onto metal nanoflake surfaces during charging must later leave those surfaces during discharge, and a single shared pathway tends to leak the stored state back out whenever the cell sits idle. The disclosed cell resolves this by routing charging and discharging through two structurally distinct paths inside one continuous dual-domain gel. Hot protons cross a hydrophobic gating region to reach the flakes during charging, while released protons exit through a hydrophilic Grotthuss channel during discharge without ever crossing that gate. Which path a hydrogen species takes is fixed by its charge state and the cell's bias state, not by any moving part or discrete membrane.

The Shared-Path Leakage Problem

In a cell that stores energy as hydrogen bonded to metal nanoflake surfaces, the storage state is only as durable as the path that hydrogen would have to take to leave. If charging and discharging both run through one common channel, that channel is also the route by which stored hydrogen can drift back off the flakes, recombine, or self-discharge while the cell sits idle. The disclosed cell separates the two operations onto two functionally distinct paths within a single continuous gel, so the path used to load hydrogen during charging is not the path available to it during storage.

Two Distinct Paths in One Continuous Gel

The gel is a dual-domain proton-conducting carbon gel: a continuous carbon framework with a hydrophilic proton-conducting domain and a hydrophobic hydrogen-rejecting domain arranged in a phase-separated nanostructure. Proton conduction through sulfonated carbon and graphene gels, and the exclusion of neutral and molecular hydrogen by hydrophobic regions, are both established behaviors in the materials literature. What the disclosure contributes is not either behavior on its own but the architecture that phase-separates the two into adjacent domains and routes charging and discharging through them as distinct paths. The metal nanoflakes reside substantially within the hydrophobic domain, while the hydrophilic channels form a continuous percolating network connecting the current collectors.

Within this gel, hydrogen species traverse two functionally distinct paths:

- A hydrophobic gating path, traversing the hydrophobic hydrogen-rejecting domains between the hydrophilic channel network and the metal nanoflake surfaces. This path is traversed during charging by hot protons under applied bias.
- A hydrophilic channel path, traversing the hydrophilic proton-conducting channels between the metal nanoflake surfaces and the current collectors. This path is traversed during discharging by released protons after bond destabilization.

The two paths are spatially distinct and pass through distinct compositional regions of the gel. Charging hot protons cross the hydrophobic gate to reach the flake. Discharging released protons enter the hydrophilic channel without crossing the hydrophobic gate.

The Hydrophobic Gate as a Kinetic Lock

That a hydrophobic region rejects neutral hydrogen and molecular hydrogen at engineering-realistic permeation rates is conventional hydrophobic and wetting chemistry, not a newly found effect. The disclosure's contribution is to position that known rejection as one of the kinetic locks holding the storage state against decay. That rejection prevents three failure modes. It prevents bonded surface hydrogen from migrating away from the flake as neutral H during storage, because the surrounding hydrophobic region rejects neutral H. It prevents surface hydrogen pairs from recombining into H_2 and escaping as gas, because the hydrophobic region rejects molecular H_2 as well as atomic H. And it prevents thermalized-proton self-charging in the absence of applied bias, because thermalized protons in the hydrophilic channels lack the energy to cross the gate and reach the flake.

The rejection is selective on charge and energy. Charged species under applied bias have sufficient potential energy to traverse the gate; charged species under thermalized conditions, and neutral species under any conditions, do not. The asymmetry between charged and neutral hydrogen species is the operating principle of the gating function.

The Hydrophilic Channel as the Egress Route

The hydrophilic channel network admits unimpeded transport of charged proton species between any two regions of the gel volume the network connects. Grotthuss-mechanism proton hopping through hydrated proton-conducting media is long-established transport physics; the disclosure does not claim it as new. During discharge, protons released at the flake enter the channel network at the hydrophilic-flake bounding interface and migrate by Grotthuss-mechanism hopping toward the opposite terminal under the potential gradient established by external circuit closure. The channel network does not block this migration and does not require an applied bias to admit it. Once a proton is released as a charged species, it proceeds through the channel without further activation. Because the released proton enters the channel directly at the flake-channel interface, the discharge path does not require crossing the hydrophobic gate at all.

Path Selection by Species and Bias State

Which path a hydrogen species follows is determined by its species identity and the cell's bias state. The disclosure sets out the following correspondence:

- A hot proton under applied charging bias traverses the hydrophobic gate, arrives at the flake surface, accepts an electron from the external charging circuit, and bonds to the flake.
- Bonded hydrogen at idle remains bonded: the electron-mediated bond is stable, and the surrounding hydrophobic region prevents alternative escape pathways.
- A released hot proton at the moment of discharge bond cleavage enters the hydrophilic channel network, migrates to the opposite terminal, and recombines with a returning electron.
- Molecular hydrogen in any state is rejected by the hydrophobic region and cannot form within the cell, because cross-flake recombination is prevented by flake-flake repulsion and same-flake recombination is suppressed by the surrounding hydrophobic region.
- A thermalized proton at idle without applied bias remains in the hydrophilic channels, lacks the energy to cross the hydrophobic gate, and does not reach the flake surfaces.

This species-specific and bias-state-specific path selection is the operating principle of the cell's charge and discharge asymmetry and the chemical basis for the storage state's stability. The distinction between a hot proton and a thermalized (cold) proton is one of energy state: a hot proton occupies a non-thermalized high-energy transit state induced by applied bias and can therefore traverse the gate, whereas a cold proton in its thermalized state cannot.

Directional Activation Zones

The gel occupies one of three operational states distinguished not by composition, which is invariant across the cell's life, but by the direction of current flow. In the charging-direction state, protons flow from the hydrophilic channel network through the hydrophobic gating regions to the flake surfaces. In the discharging-direction state, protons flow from the flake surfaces into the hydrophilic channel network and toward the opposite terminal. In the equipotential storage state, no current flows and the directional asymmetries are absent.

The disclosure describes the active path of each direction as an activated, or light, zone and the passive path as a deactivated, or dark, zone. In the charging-direction state the hydrophobic gating regions are the activated zone and the hydrophilic channels are the passive reservoir. In the discharging-direction state those roles reverse: the hydrophilic channels become the activated zone and the hydrophobic gate becomes the deactivated zone. This convention is independent of any visible-light illumination and refers to which structural features are mediating active flow as a function of current direction.

How This Differs from a Membrane Separator

The disclosure distinguishes this asymmetry from conventional membrane-based asymmetry on four points. The asymmetry is created by structural domains within a single continuous gel medium rather than by a discrete physical membrane. It is selective on species charge and bias state rather than on species size or geometry alone. It admits both ingress and egress through the same gel volume but via spatially distinct paths, rather than gating every species through one common path. And it is co-located with the flake population, providing per-flake gating rather than cell-wide separator gating.

Disclosure Scope

This article describes subject matter disclosed in U.S. Provisional Application No. 64/055,649. The provisional is an early-stage disclosure that sets out concepts and mechanisms, in many places without specific numerical values. Nothing here should be read as a claim of measured performance, and no value, threshold, or material property is asserted beyond what the application itself discloses.

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)

APPLICATIONS · GENERAL

- Grid-Scale and Renewable-Firming Storage with the Hydrogen-Aluminum Energy Cell (/articles/h-al-battery/grid-scale-storage)
- Building-Integrated and Behind-the-Meter Storage: Putting Energy Cells Inside the Structure With the Hydrogen-Aluminum Energy Cell (/articles/h-al-battery/building-integrated-storage)
- Stationary Backup and UPS Reserve Power for Data Centers, Hospitals, and Telecom (/articles/h-al-battery/backup-and-ups)
- Storage for Microgrids, Islands, and Off-Grid Sites: A Stationary Cell Built From Abundant Materials (/articles/h-al-battery/microgrid-and-off-grid)
- Electric Mobility and Transport: How a Hydrogen-Aluminum Cell Architecture Maps to Vehicle Constraints, and Where It Does Not (/articles/h-al-battery/ev-and-mobility)
- Marine and Rail Energy Storage: A Bulk-Equipotential Hydrogen-Aluminum Cell for Mass-Tolerant Heavy Transport (/articles/h-al-battery/marine-and-rail)

- Supply-Chain-Resilient Field Power: An Abundant-Material Energy Cell for Defense and Expeditionary Operations (/articles/h-al-battery/defense-and-field-power)
- Fast-Response Frequency Regulation and Power Quality Without a Separate Power Bank (/articles/h-al-battery/frequency-regulation-power-quality)

APPLICATIONS · SPECIFIC

- CATL (Contemporary Amperex Technology Co. Limited) alternative: a hydrogen-aluminum cell architecture vs LFP, NMC, and sodium-ion at the chemistry-category and materials-sourcing level (/articles/h-al-battery/catl)
- LG Energy Solution NCM/NCMA lithium-ion cells vs the Hydrogen-Aluminum Energy Cell: an architectural comparison (/articles/h-al-battery/lg-energy-solution)
- Form Energy iron-air multi-day grid storage vs a sealed bulk-equipotential hydrogen-aluminum cell: an architectural comparison (/articles/h-al-battery/form-energy)
- ESS Inc, maker of long-duration iron flow batteries vs a sealed solid-state cell: comparing the flow architecture to the Hydrogen-Aluminum Energy Cell (/articles/h-al-battery/ess-inc)
- Ambri liquid-metal battery vs a solid-state hydrogen-aluminum energy cell: architectural comparison for stationary storage (/articles/h-al-battery/ambri)
- QuantumScape solid-state lithium-metal battery vs a bulk-equipotential hydrogen-aluminum surface-bond cell: an architecture comparison (/articles/h-al-battery/quantumscape)
- Natron Energy sodium-ion (Prussian-blue-electrode) batteries vs a hydrogen-aluminum surface-bond cell: an abundant-materials architecture comparison (/articles/h-al-battery/natron-energy)
- Eos Energy Enterprises Znyth zinc long-duration storage vs a hydrogen-aluminum equipotential cell: an abundant-materials architecture comparison (/articles/h-al-battery/eos-energy)
- EnerVenue nickel-hydrogen stationary cells vs a hydrogen-aluminum equipotential cell: two ways to store hydrogen in a battery (/articles/h-al-battery/enervenue)
- Skeleton Technologies supercapacitors vs the Hydrogen-Aluminum Energy Cell: pairing high power with bulk energy storage (/articles/h-al-battery/skeleton-technologies)

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