

Hot-Proton Charging Versus Cold-Proton Discharge: The Bias-Gated Asymmetry That Blocks Self-Charge and Self-Discharge

This article documents the hot-proton-charging-versus-cold-proton-discharge asymmetry, a secondary inventive step of the Hydrogen-Aluminum Energy Cell disclosed in U.S. Provisional Application No. 64/055,649, and the asymmetric dual-domain ingress and egress paths through which it operates. A storage cell that holds energy as metal-hydrogen surface bonds must keep those bonds from forming or breaking on their own, or it leaks charge while sitting idle. The disclosed hydrogen-aluminum cell solves this with a charging-versus-discharging path asymmetry built into a dual-domain gel. Charging requires bias-induced hot protons that carry enough energy to cross a hydrophobic gating region and reach the flake surface, where they accept an electron through proton-coupled electron transfer and bond. Thermalized ground-state protons sitting in the hydrophilic channels lack that energy and cannot cross the gate, so no bonding occurs without applied bias. Discharge runs a different path entirely: load-driven electron drain destabilizes the bond, the released hot proton enters the hydrophilic channel directly at the flake-channel interface without crossing the hydrophobic gate,

thermalizes by Grotthuss hopping, and migrates to the opposite terminal. The result is a cell whose storage state is kinetically locked against both thermalized self-charging and self-discharging.

The Idle-Leakage Problem in Surface-Bond Storage

A cell that stores energy as electron-stabilized metal-hydrogen surface bonds faces a basic risk: if those bonds can form or break without an external driver, the cell charges or discharges itself while sitting idle. Each of the underlying pieces here is established science. Chemisorption of atomic hydrogen on aluminum and similar metal surfaces, proton-coupled electron transfer, and proton transport in sulfonated carbon gels are all well characterized in the literature. The novelty is not any of these effects but the architecture that combines them into a reversible cell and the path asymmetry described below that keeps the storage state from drifting on its own. The disclosed cell stores energy as atomic hydrogen bonded to surface metal atoms on metal nanoflakes, with each bond formed during charging by proton-coupled electron transfer and reversed during discharging by withdrawal of the bonding electron. For that storage to be useful, two unwanted spontaneous reactions must be suppressed: thermalized protons should not be able to drift to a flake and bond on their own (self-charging), and bonded hydrogen should not be able to leave the flake on its own (self-discharging). The disclosed mechanism addresses both by making the charging path and the discharging path traverse different regions of the gel under different energy conditions.

Charging: Hot Protons Across a Hydrophobic Gate

During charging, the proton arriving at the flake surface is in a high-energy transit state induced by the applied bias rather than in a thermalized ground state. That a biased proton carries more energy than a thermalized one, and that hydrophobic regions reject neutral and molecular hydrogen, are both conventional. What the disclosed cell does is

configure those known behaviors as a gate: this hot-proton state has sufficient energy to overcome the flake's repulsive surface potential and to traverse the hydrophobic gating region that separates the hydrophilic channel network from the flake surfaces. On reaching the flake, the hot proton accepts an electron arriving from the external charging circuit, and the proton and electron combine through proton-coupled electron transfer, an established reaction, to form an atomic hydrogen species bonded to a surface metal atom by a covalent or polar-covalent metal-hydrogen bond.

Why Thermalized Protons Cannot Charge the Cell

Without applied bias, thermalized ground-state protons in the gel lack the energy to reach a flake surface, and no hydrogen bonding occurs. The hydrophobic gating region rejects neutral hydrogen and molecular hydrogen at engineering-realistic permeation rates, and its rejection is selective on charge and bias state: charged species under applied bias have sufficient potential energy to traverse the gate, while charged species under thermalized conditions and neutral species under any conditions do not. So a thermalized proton sitting in the hydrophilic channels at idle remains there, lacks the energy to cross the hydrophobic gate, and does not reach a flake surface. This is the kinetic basis for the storage state's stability against thermalized self-charging.

Discharge: Cold-Proton Egress Through the Hydrophilic Channel

Discharging runs the inverse process but not the inverse path. External load drain removes the bonding electron from the metal-hydrogen bond. The now-unstable bond releases the hydrogen as a hot proton at the moment of bond cleavage, carrying the bond-energy excess as kinetic and electronic excitation, and that proton enters the hydrophilic channel network directly at the flake-channel interface. The discharge path does not require crossing of the hydrophobic gating region. Once in the channel network, the released proton rapidly thermalizes through Grotthuss-mechanism hopping, the ordinary proton-transport mechanism in such gels, and migrates to the

opposite terminal, where it picks up an electron returning through the external load circuit and re-equilibrates as a charge-balanced proton in the gel. The hydrophilic channel admits unimpeded transport of charged proton species between connected regions of the gel and requires no applied bias to admit that migration: once the proton is released as a charged species, it proceeds without further activation.

The Two Paths Are Spatially Distinct

The charging and discharging routes traverse distinct compositional regions of the gel. The charging path is a hydrophobic gating path that crosses the hydrophobic hydrogen-rejecting domains between the hydrophilic channel network and the flake surfaces, traversed during charging by hot protons under applied bias. The discharging path is a hydrophilic channel path between the flake surfaces and the current collectors, traversed during discharge by released protons after bond destabilization. Charging hot protons cross the hydrophobic gate to reach the flake; discharging released protons enter the hydrophilic channel without crossing it. Because the gating is co-located with the flake population, it provides per-flake gating rather than cell-wide separator gating.

Path Selection by Species and Bias State

The disclosed cell selects a path for each hydrogen species according to its charge and the bias state, with a defined correspondence. A hot proton under applied charging bias traverses the hydrophobic gate, arrives at the flake surface, accepts an electron, and bonds. Bonded hydrogen at idle remains bonded, since 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 the returning electron. Molecular hydrogen at any state is rejected by the 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 high stability.

The Gating Asymmetry as One of Several Kinetic Locks

The hydrophobic gate's rejection of neutral and molecular hydrogen is one of multiple kinetic locks that hold the storage state against decay. That rejection prevents migration of bonded surface hydrogen as neutral hydrogen away from the flake during storage, prevents recombination of surface hydrogen pairs into molecular hydrogen with subsequent gas-phase escape, and prevents thermalized-proton self-charging in the absence of applied bias. The asymmetry between charged and neutral hydrogen species is what makes the gate work: it discriminates by species charge and bias state, not by species size or geometry. That a hydrophobic barrier passes a field-driven charged species while blocking neutral and molecular hydrogen is conventional electrochemistry; the disclosed contribution is co-locating that known discrimination with each flake so it functions as a kinetic lock rather than as a bulk membrane property. This kinetic gating works alongside the electron-mediated stability of the bond itself, under which the bonding electrons remain in place in the absence of load, so the bond neither spontaneously decomposes nor requires continuous bias for maintenance.

How Boron Doping Sharpens the Discrimination

Boron is the standard p-type dopant for carbon electronic materials, and its effects on boron-doped graphene, including modified electronic properties and increased specific surface area, are documented in the literature. The disclosed cell applies that known dopant as a precision multiplier: boron doping at the hydrophilic-hydrophobic domain boundaries gives sharper definition of those boundaries than undoped embodiments, and this directly improves the kinetic gating by admitting cleaner discrimination

between hot and thermalized proton species. The energy threshold separating thermalized-proton-blocked behavior from hot-proton-passing behavior becomes more sharply defined. That sharpening admits lower charging-bias requirements for hot-proton ingress while admitting tighter retention of thermalized protons in the absence of bias, with the disclosure stating charging at approximately 1.4 to 2.0 volts in such embodiments versus approximately 1.8 to 2.5 volts in undoped embodiments, and reduced self-discharge rates at extended storage durations. Boron sites within the currently activated zone also participate in proton mediation and electron transfer at higher rates than boron sites in the deactivated zone, contributing to the asymmetric kinetic gating.

Disclosure Scope

This article describes subject matter disclosed in U.S. Provisional Application No. 64/055,649. It is a technical description of disclosed mechanisms and embodiments and is not a claim construction, a legal opinion, or a representation of granted rights. A provisional application establishes a priority date and is not examined; the scope of any resulting protection depends on claims prosecuted in a corresponding nonprovisional application.

Hydrogen-Aluminum Energy Cell [\(/h-](#) [All 40 steps → \(/inventive-steps\)](#)

al-battery)

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 \(/articles/h-al-battery/bulk-equipotential-charge-retention\)](/articles/h-al-battery/bulk-equipotential-charge-retention)
- [Storing Energy as Electron-Stabilized Metal-Hydrogen Surface Bonds Formed by Proton-Coupled Electron Transfer \(/articles/h-al-battery/hydrogen-metal-surface-bond-storage\)](/articles/h-al-battery/hydrogen-metal-surface-bond-storage)
- [Electron-Mediated Bond Stability: The Kinetically Trapped Idle State Behind Indefinite Calendar Life \(/articles/h-al-battery/electron-mediated-bond-stability\)](/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 \(/articles/h-al-battery/hot-cold-proton-asymmetry\)](/articles/h-al-battery/hot-cold-proton-asymmetry)**
- [Asymmetric Dual-Domain Proton Paths: Separate Ingress and Egress Routes in a Hydrogen-Aluminum Storage Gel \(/articles/h-al-battery/asymmetric-dual-domain-paths\)](/articles/h-al-battery/asymmetric-dual-domain-paths)
- [Hydrophobic Gating: Rejecting Neutral and Molecular Hydrogen While Admitting Only Biased Protons \(/articles/h-al-battery/hydrophobic-gating\)](/articles/h-al-battery/hydrophobic-gating)
- [The Storage Gel as a Polarized Electrochemical Switch: Coherent Alignment, Equipotential Locking, and Load-Proportional Discharge \(/articles/h-al-battery/gel-polarized-switch\)](/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 \(/articles/h-al-battery/flake-electrostatic-isolation\)](/articles/h-al-battery/flake-electrostatic-isolation)
- [Dynamic Flake Expansion: Carbon-Intercalation Wedging to Expose Buried Metal Surface Under Bias \(/articles/h-al-battery/dynamic-flake-expansion\)](/articles/h-al-battery/dynamic-flake-expansion)
- [Hydrogen-Locked Expanded State: Surface-Energy Inversion as a Positive-Feedback Capacity Mechanism \(/articles/h-al-battery/hydrogen-locked-expanded-state\)](/articles/h-al-battery/hydrogen-locked-expanded-state)
- [Secondary Carbon-Hydrogen Storage on Transmuted Intercalated Carbon \(/articles/h-al-battery/secondary-carbon-hydrogen-storage\)](/articles/h-al-battery/secondary-carbon-hydrogen-storage)
- [Mechanochemical Strain Self-Healing and Use-Positive Aging in a Bulk-Equipotential Hydrogen-Aluminum Cell \(/articles/h-al-battery/mechanochemical-self-healing\)](/articles/h-al-battery/mechanochemical-self-healing)
- [Boron Doping of the Carbon Framework as a Multi-Function Precision Multiplier \(/articles/h-al-battery/boron-doping-precision-multiplier\)](/articles/h-al-battery/boron-doping-precision-multiplier)
- [The Floating Aluminum Equipotential Extension Layer: A Multifunctional Inner Case for the Bulk-Equipotential Cell \(/articles/h-al-battery/aluminum-equipotential-extension-layer\)](/articles/h-al-battery/aluminum-equipotential-extension-layer)

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