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Storing Energy as Electron-Stabilized Metal-Hydrogen Surface Bonds Formed by Proton-Coupled Electron Transfer

This article documents hydrogen-metal surface-bond storage via proton-coupled electron transfer, a secondary inventive step of the Hydrogen-Aluminum Energy Cell disclosed in U.S. Provisional Application No. 64/055,649, and the related mechanisms of electron-mediated bond stability that give the cell a kinetically trapped idle state and the hot-proton charging versus cold-proton discharge asymmetry that keeps that state stable. Conventional ways of holding hydrogen as an energy carrier each carry a structural penalty: bulk metal hydride formation buries hydrogen in interstitial lattice sites throughout the metal volume and pays for it with slow bulk-lattice diffusion and lattice strain; physisorption holds hydrogen only weakly by van der Waals interactions without a chemical bond; and intercalation parks a storage species between host-lattice layers. The disclosed cell takes a different path. It stores electrical energy as electron-stabilized metal-hydrogen surface bonds formed at the surfaces of metal nanoflakes by proton-coupled electron transfer, in which a proton arriving from the gel and an electron arriving from the external circuit combine at a flake surface to bond an atomic hydrogen to a surface metal atom. The bond exists only while its bonding electron pair is present, so removing the electron through a load is the direct trigger for release. This surface-

> bond chemistry aims to capture the bond strength of hydride formation without the lattice-strain consequences, and the storage density of bulk hydrides without the bulk-diffusion kinetic limits.

The Storage Problem This Mechanism Solves

A hydrogen energy carrier has to be held somewhere, and each established option forces a trade. Bulk metal hydride formation, in which hydrogen occupies interstitial lattice sites throughout the metal volume, gives a strong chemical bond and high density, but the hydrogen has to diffuse through the bulk lattice and the filled lattice strains the host. Physisorbed hydrogen on porous surfaces is held only by van der Waals interactions, with no chemical bond and therefore weak retention. Intercalation chemistry places the storage species in host-lattice sites between layers of the host material, which again ties storage to a structural lattice.

Atomic hydrogen chemisorption on aluminum and analogous metal surfaces is established surface science, characterized in the literature at binding energies in the range of roughly 50 to 100 kilojoules per mole. What is novel here is not that chemistry but the architecture that harnesses it: the disclosed cell stores energy as electron-stabilized metal-hydrogen surface bonds on metal nanoflakes and operates that surface bonding as a reversible charge-storage chemistry inside a sealed equipotential cell. The spec frames this storage mode as explicitly distinct from all three of the above. The intent stated in the disclosure is to admit the high-density storage of bulk metal hydrides without the kinetic limitations of bulk-lattice diffusion, and to admit the chemical bond strength of metal hydride formation without the lattice-strain consequences thereof.

Proton-Coupled Electron Transfer at the Flake Surface

Proton-coupled electron transfer is a well-characterized reaction class, and atomic hydrogen bonding to a metal surface is established chemisorption; the cell does not invent either. Its contribution is to wire those known steps together as the charge and discharge half-reactions of a battery. During charging, the bonds form by proton-coupled electron transfer at the flake surfaces. A proton arriving from the gel and an electron arriving from the external charging circuit combine at the flake surface to form an atomic hydrogen species bonded to a surface metal atom by a covalent or polar-covalent metal-hydrogen bond. The reaction is reversed during discharging by the inverse process: the electron is withdrawn through the external load circuit and the bonded hydrogen reverts to a proton released into the gel.

The disclosure defines the resulting bond directly. An "electron-stabilized metal-hydrogen surface bond" means a covalent or polar-covalent bond between a surface metal atom of a metal nanoflake and a chemisorbed hydrogen atom, the bond being stable in the presence of the bonding electron pair and unstable in the absence of that bonding electron pair.

The cell also admits optional catalyst sites distributed across the metal nanoflake surfaces and at the hydrophilic-hydrophobic domain interfaces within the gel, configured to lower the activation energies for the proton-coupled electron transfer reactions during both charging and discharging.

Why It Is Not Hydride, Physisorption, or Intercalation

The distinction is structural, not just terminological. In bulk hydride formation the hydrogen lives in interstitial sites through the metal volume; here the hydrogen is bonded at the surface of a thin nanoflake. In physisorption the hydrogen is held without a chemical bond; here the bond is covalent or polar-covalent. In intercalation the storage species sits between host-lattice layers; here there is no host-lattice intercalation of the hydrogen at all.

Because storage is at the surface rather than in the bulk, the hydrogen does not have to diffuse through a metal lattice to be stored or recovered, which the spec presents as removing the kinetic bottleneck of bulk-diffusion systems while keeping a real chemical bond.

Electron-Mediated Bond Stability

That a covalent or polar-covalent bond depends on its shared bonding electron pair is ordinary chemistry, not a new discovery. The disclosure's contribution is to operate that dependence as a control scheme: the bond is electron-stabilized, existing by virtue of the bonding electron pair shared between the metal atom and the hydrogen atom, so removal of the bonding electrons by external load drain destabilizes the bond and releases the hydrogen as a proton. Configured this way, load-driven electron drain becomes the proximate trigger for hydrogen release, with the gel providing the proton-receiving environment without itself driving the discharge.

The same property gives an idle-state stability. In the absence of external load, the bonding electrons remain in place and the bond is stable. The disclosure states the bond does not spontaneously decompose and does not require continuous external bias for maintenance; it is described as a kinetically trapped excited state stabilized by the bonding electrons and by the gel's prevention of alternative decay pathways. The spec ties this idle stability to the calendar-life property recited elsewhere in the disclosure.

Where the Bonds Sit on the Flake

That edge, defect, and high-curvature surface sites bind adsorbed hydrogen more strongly than flat basal-plane sites is established surface science; the cell exploits it by engineering the flake population for those sites. Hydrogen bonding is preferentially localized at edge sites, defect sites, dopant-adjacent sites, and high-curvature surface sites on the metal nanoflakes. These preferential sites exhibit lower hydrogen-binding activation energies and stronger metal-hydrogen bonds than flat low-index basal-plane sites. The disclosure notes that engineering the flake population to maximize preferential-site density admits higher storage capacity per unit metal mass and more favorable charging and discharging kinetics.

Listed methods of engineering that site density include flake size reduction (smaller flakes admit a higher edge fraction), defect introduction by mechanical or chemical processing, dopant introduction during flake synthesis (boron, nitrogen, transition-metal dopants), and crystallographic orientation control during synthesis.

A Distribution of Bond Energies

The binding sites across the flake population exhibit a distribution of bond energies rather than a single discrete value. The disclosure attributes this to structural non-uniformity: each flake's unique edge geometry, defect population, and dopant content presents a unique constellation of binding sites at slightly different binding energies. The disclosure states this distribution admits a smooth voltage discharge profile and robustness against local thermal or electrochemical hot spots, because no single resonant binding-site population dominates the cell's behavior.

Hot-Proton Charging and Cold-Proton Discharge

Bias-driven proton transport and thermalized proton hopping are both known transport regimes; the novelty is the asymmetric path that routes charging and discharging through them differently. Charging proceeds with the proton in a high-energy transit state induced by the applied bias rather than in a thermalized ground state. This hot proton has sufficient energy to overcome the flake's repulsive surface potential and to traverse the hydrophobic gating region of the gel. Without applied bias, thermalized ground-state protons in the gel lack the energy to reach a flake surface, so no hydrogen bonding occurs. The disclosure presents this as the kinetic basis for the storage state's stability against thermalized self-charging or self-discharging.

Discharging is the inverse. External load drain removes the bonding electron, the now-unstable bond releases the hydrogen as a hot proton at the moment of cleavage carrying the bond-energy excess as kinetic and electronic excitation, and that proton enters the hydrophilic channel network of the gel directly at the flake-channel interface. The released proton then thermalizes through Grotthuss-mechanism hopping and migrates to the opposite terminal, where it picks up an electron returning through the external load and re-equilibrates as a charge-balanced proton in the gel. The disclosure notes that the discharge path does not require crossing the hydrophobic gating region, which is the asymmetry between the charging and discharging paths.

Disclosure Scope

This article describes subject matter disclosed in U.S. Provisional Application No. 64/055,649. A provisional application is an early-stage filing that discloses concepts and mechanisms and is not an issued patent. The mechanism described here, energy storage as electron-stabilized metal-hydrogen surface bonds formed by proton-coupled electron transfer, is presented as disclosed in that application, including its stated distinctions from bulk metal hydride formation, physisorption, and intercalation. Nothing here should be read as a claim of issued patent rights or as a representation of performance beyond what the application 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)

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