A Hydrogen–Aluminum Surface-Bond Storage Cell with Bulk-Equipotential Charge Retention in a Proton-Conducting Carbon Gel

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1. Introduction

Conventional rechargeable cells share a common architectural assumption. An anode and a cathode at distinct electrochemical potentials are separated by an ion-conducting and electronically-insulating barrier — the separator, the membrane, or the solid-electrolyte phase — whose integrity is the load-bearing mechanism for charge retention. Lithium-ion cells, sodium-ion cells, lead-acid cells, nickel-metal-hydride cells, lithium-sulfur cells, metal-air cells, and redox-flow cells all conform to this architecture. The separator's failure modes — mechanical breach, dendrite penetration, electrolyte breakdown — are the principal determinants of cell safety and cycle life across the entire incumbent industry.

We describe a different architecture. The interior of the disclosed cell is a single continuous medium with both electronic and ionic conductivity, mechanically continuous from one terminal to the other. There is no internal separator. Charge retention is achieved through a different principle, which we refer to as bulk-equipotential saturation. In the storage state, the conductive gel medium equilibrates every storage site to a common electrochemical potential, and the absence of any internal gradient removes the driving force for internal current flow. The cell holds its charge not by being insulated against current but by being internally saturated to the point that no thermodynamic gradient exists for current to follow.

The active material is metallic aluminum, dispersed as nanoparticles throughout the gel volume. The storage chemistry is the well-known surface chemisorption of atomic hydrogen on aluminum surfaces: a covalent metal-hydrogen bond stabilized by an electron pair shared between a surface metal atom and a hydrogen atom. Charging proceeds through proton-coupled electron transfer at the metal surface; discharging proceeds by the reverse process, with electron drain through an external load destabilizing the bond and releasing the hydrogen as a proton. Aluminum is not consumed across cycles; the cycle is conservative in mass and benign in chemistry.

This article develops the mechanism-level design of the cell, derives its projected energy density from first-principles surface chemistry, situates the architecture in the context of incumbent electrochemical storage, and identifies the open empirical questions that prototype testing must answer. The intent is to publish the architecture in a form sufficient to support technical-audience review and experimental replication without exhausting the inventive content of the underlying patent filings, which include synthesis-route specifics, additive selection, conditioning protocols, and several architectural enhancements that we retain as trade secret.

2. Prior Art at the Component Level

Each load-bearing mechanism of the disclosed architecture has published prior art at the materials-science level. The novelty of the disclosure is in the integration of these mechanisms into a single sealed cell with bulk-equipotential charge retention as the operating principle.

The chemisorption of atomic hydrogen on aluminum surfaces has been characterized in surface-science research since the 1970s. Density-functional calculations and ultrahigh-vacuum experimental studies have established hydrogen binding energies on the principal aluminum crystallographic faces in the range of approximately 50 to 80 kilojoules per mole, with site-dependent variation determined by surface coordination and local electronic structure. Edge sites, defect sites, and dopant-adjacent sites exhibit lower activation energies and stronger bonds than flat basal-plane sites, admitting the use of structurally-defected aluminum nanoparticles to maximize accessible binding-site density per unit mass.

Sulfonated carbon gels — including sulfonated reduced graphene oxide gels, sulfonated graphene aerogels, and sulfonated turbostratic carbon gels — have been characterized in the published literature since approximately 2010. Reported proton conductivities at engineering-realistic hydration are in the range of 0.05 to 0.20 siemens per centimeter, comparable to perfluorinated sulfonic-acid polymers used as fuel-cell membranes. Unlike polymer-based proton-conducting media, these carbon-framework gels exhibit electronic conductivity in the range of 0.1 to 100 siemens per centimeter in the carbon network itself, admitting combined ionic and electronic conduction in a single material. This combined conductivity is foundational to the bulk-equipotential charge retention mechanism described here.

The mutual electrostatic repulsion of like-charged colloidal particles is described by classical DLVO theory (Derjaguin and Landau, 1941; Verwey and Overbeek, 1948), which characterizes the balance between van der Waals attraction and electrostatic double-layer repulsion in stabilizing colloidal dispersions. For metal nanoparticles dispersed in a charged gel medium, contact equilibration of surface charge with the surrounding framework leads to like-charged surface potentials that maintain inter-particle spacing through electrostatic repulsion. We invoke this mechanism to suppress cross-particle hydrogen recombination — a structurally distinct prevention mechanism from the chemical encapsulation approaches employed in core-shell nanoparticle architectures.

The morphological response of metal nanoparticles to applied electrochemical bias has been characterized in published research since approximately 2014, in the context of battery anode materials, electrocatalysis, and 2D-materials synthesis. Carbon intercalation between metallic layers, and the formation of metal-carbon adsorption complexes at metal surfaces, are similarly well-characterized. Hydrogen physisorption and chemisorption in nanoporous carbon hosts has been characterized extensively in U.S. Department of Energy hydrogen-storage research programs since the early 1990s. The disclosed architecture is distinct in that hydrogen is held in chemisorption-class bonds at the metal nanoparticle surfaces rather than at the carbon framework's surfaces, with the carbon framework serving as the conductive medium rather than as the storage medium.

3. Cell Architecture

The disclosed cell comprises a hermetically sealed enclosure containing a continuous proton-conducting carbon gel that fills the entire interior volume. Two carbon current collectors are disposed at opposite faces of the enclosure and are in Ohmic contact with the gel. Aluminum nanoparticles are dispersed throughout the gel volume. Electrical terminals exit the enclosure through hermetic dielectric feedthrough seals. There is no internal separator, no internal membrane, and no internal physical barrier between the two current collectors other than the gel volume itself.

The enclosure inner surface comprises an electrically conductive metallic layer — aluminum is the preferred embodiment — in Ohmic contact with the gel and electrically isolated from the cell's external terminals via the hermetic feedthroughs. The conductive inner layer floats at the gel's bulk equipotential potential, extending the equipotential volume of the cell to include the enclosure inner surface. This eliminates a class of external parasitic-discharge pathways that would otherwise admit slow leakage through the enclosure dielectric, and provides electromagnetic shielding of the cell interior. The outer-facing surface of the aluminum layer naturally passivates with a thin Al_2O_3 layer, providing an oxygen barrier without active getter chemistry.

The bulk gel composition comprises two principal compositional domains in a phase-separated nanostructured arrangement within a continuous carbon framework. Hydrophilic regions functionalized with proton-donating groups (sulfonate, phosphonate, carboxylate) admit Grotthuss-mechanism proton conduction at conductivities in the 0.01 to 0.30 S/cm range. Hydrophobic regions functionalized with non-protogenic groups (fluorinated functionalities, alkyl chains) reject neutral hydrogen and molecular hydrogen at engineering-realistic permeation rates. The continuous carbon framework provides electronic conductivity in the 0.1 to 100 S/cm range throughout the gel volume.

The dispersed metal nanoparticles have characteristic dimensions in the range of approximately 1 to 50 nanometers thickness and 5 to 500 nanometers lateral dimension. Aluminum is the preferred embodiment by virtue of its low atomic mass, low cost, abundance, and binding-energy compatibility with the operating chemistry. The particles carry like surface charge through contact equilibration with the gel's framework, which produces mutual electrostatic repulsion in accordance with DLVO theory and maintains inter-particle spacing throughout the operational lifetime. Aluminum mass loading is typically in the range of 30 to 50 percent of total cell mass.

4. Storage Chemistry

During charging, an applied electrochemical bias drives a proton-coupled electron transfer reaction at the metal nanoparticle surface. A proton arriving from the gel and an electron arriving from the external charging circuit combine at the aluminum surface to form an atomic hydrogen species bonded to a surface aluminum atom. The resulting metal-hydrogen bond is a covalent or polar-covalent bond stabilized by the bonding electron pair, with binding energy determined by the local surface coordination and electronic structure.

Hydrogen binding is preferentially localized at edge sites, defect sites, and dopant-adjacent sites on the nanoparticles, where surface coordination is reduced and electronic structure is more reactive. Engineering of the nanoparticle population to maximize the density of such preferential sites — through controlled defect introduction, dopant incorporation, and morphological tuning during synthesis — increases per-mass storage capacity and admits more favorable charge-discharge kinetics.

Discharge proceeds by the reverse process. External load drains electrons from the metal-hydrogen bond through the gel's electronic conduction network. The bond destabilizes; the hydrogen atom reverts to a proton at the moment of bond cleavage, carrying the bond-energy excess as kinetic and electronic excitation; the proton enters the hydrophilic channel network of the gel and migrates through Grotthuss-mechanism hopping toward the opposite terminal, where it recombines with an electron returning through the external circuit to maintain charge balance. The aluminum particle returns to its ground state. No metal is consumed; no aluminum hydride bulk phase forms; the cycle is geometric, not transformative.

5. Bulk-Equipotential Charge Retention

The bulk-equipotential charge retention principle is, to our knowledge, novel as the load-bearing mechanism of an electrochemical storage cell. We characterize it here at the level of mechanism and contrast it with conventional separator-based retention.

When the cell is charged and the external circuit is open, the aluminum nanoparticle population is in an equipotential condition. All particles are at substantially the same electrochemical potential. Any local potential difference between two regions of the gel is rapidly equalized through the gel's combined electronic and ionic conductivity, with the equilibration timescale being short relative to the cell's storage timescale. In the equipotential condition, no internal driving force exists for charge to redistribute within the cell; the cell is internally at rest despite holding stored chemical energy in the metal-hydrogen bonds at the particle surfaces.

A conventional rechargeable cell holds its charge because the anode and cathode are at distinct potentials and the separator prevents electron flow between them. Any breach of the separator results in self-discharge through the breach. The disclosed cell holds its charge through a different mechanism: there is no potential difference to equalize across, because every storage site is at the same potential. The cell is internally short-circuited by design — its bulk medium is conductive end-to-end — and it holds its charge not in spite of this but because of it. Charge cannot flow in the absence of a thermodynamic gradient, and the equipotential storage state has no such gradient.

Closure of an external circuit between the two terminals through a load creates an asymmetric path: electrons may exit the cell at one terminal, traverse the load, and re-enter at the opposite terminal. This establishes a potential gradient across the gel volume — the regions near the exit terminal become depleted of electrons and drop in potential, while the regions near the entry terminal remain at the storage potential. The gradient drives internal redistribution of stored charge toward the exit terminal, where electrons are released to the load. The cell discharges only as fast as the external load admits; in the limiting case of an open circuit, the cell does not discharge at all.

The equipotential storage state is intrinsically robust against internal self-discharge, because the absence of an internal gradient removes the driving force for internal redistribution. External parasitic pathways such as capacitive leakage through the enclosure dielectric are addressed by the conductive inner layer of the enclosure, which extends the equipotential volume to include the enclosure inner surface and removes the dielectric-boundary parasitic path.

6. Asymmetric Hydrogen Ingress and Egress

Hydrogen species traverse two functionally distinct paths within the dual-domain gel during charging and discharging. The said two paths are spatially distinct and traverse distinct compositional regions of the gel.

Under applied charging bias, protons in the hydrophilic channels are accelerated by the bias-induced potential gradient and acquire excess kinetic and electronic energy, entering a non-thermalized high-energy state. This bias-induced excitation provides the energy required for the said protons to traverse the hydrophobic regions of the gel between the channel network and the metal nanoparticle surface. Without applied bias, thermalized protons in the channels lack the energy to cross the hydrophobic region and do not reach the particle surfaces.

When external load drains electrons from the metal-hydrogen bond, the bond destabilizes and the hydrogen atom is released as a proton at the surface. The released proton — a charged species — is welcome in the hydrophilic channels and migrates through them by Grotthuss-mechanism hopping toward the opposite terminal. The released proton does not need to cross the hydrophobic gate on the way out: the charging path and the discharging path are structurally distinct, and the discharging path is energetically downhill for charged species at all points.

The hydrophobic regions reject both neutral atomic hydrogen and molecular H_2 at engineering-realistic permeation rates. This rejection provides one of the multiple kinetic locks holding the storage state against decay: bonded surface hydrogen cannot escape as neutral hydrogen because the surrounding hydrophobic region is impassable; two hydrogen atoms on adjacent sites cannot recombine and escape as H_2 for the same reason; thermalized protons in the channels cannot self-ingress without applied bias because the bias-acquired energy is required for gate traversal.

7. Energy Density Projection

Per the surface chemistry, hydrogen storage capacity is determined by the surface atom density of aluminum, the fraction of surface atoms participating in hydrogen binding, and the total particle surface area per unit mass. For a representative aluminum nanoparticle of 2 to 5 nanometers thickness with lateral dimensions on the order of 50 to 100 nanometers, surface atoms constitute approximately 15 to 40 percent of total particle atoms, depending on geometry. At substantially monolayer hydrogen coverage, the corresponding hydrogen-to-aluminum atomic ratio is approximately 0.15 to 0.40, which translates to a specific capacity in the range of approximately 150 to 400 milliampere-hours per gram of aluminum ($Q_{spec} = (H \text{ per } Al) \times F / M(Al)$).

Combined with a mean discharge voltage of approximately 1.8 to 2.4 volts — set by the metal-hydrogen bond energy and the proton-coupled electron-transfer thermodynamics — the per-metal energy density projection is approximately 270 to 960 watt-hours per kilogram of aluminum active mass. Cell-level energy density is the per-metal energy density multiplied by the metal mass fraction of the total cell mass. With aluminum loading in the 30 to 50 percent mass-fraction range and accounting for the mass of the gel, current collectors, enclosure, and electrical terminals, the projection settles in the 200 to 500 watt-hours per kilogram cell-level envelope.

For context, commercial lithium-ion cells at present commercial state of art achieve approximately 200 to 300 watt-hours per kilogram cell-level energy density. Next-generation lithium-metal cells in development project 300 to 500 watt-hours per kilogram cell-level on the 2027 to 2030 horizon. Lithium-air cells project theoretical limits of approximately 5,000 watt-hours per kilogram but in practice achieve a small fraction of this owing to cycle-life and kinetic limitations. Aluminum-air cells project theoretical 8,000 watt-hours per kilogram but require atmospheric oxygen ingress and exhibit extreme calendar-life challenges in sealed configurations.

The disclosed cell's projected envelope places it at parity with mature lithium-ion at its lower edge and competitive with aspirational lithium-metal at its upper edge, achieved through a sealed, oxygen-excluding architecture that does not require atmospheric ingress or exotic cathode chemistry. The architecture is positioned in a regime that is empirically tractable, materially conservative, and competitively meaningful — rather than chasing theoretical maxima that incumbent chemistries have demonstrated to be practically unrealizable.

8. Charge–Discharge Operation

Charging is initiated by applying a positive bias to one terminal relative to the other from an external power source. The bias drives current flow into the cell and creates a potential gradient across the gel, concentrated at the hydrophilic channel network. Protons in the channels are accelerated by the gradient and acquire excess energy, entering the hot-proton state. Hot protons traverse the hydrophobic regions to the metal nanoparticle surfaces, where they combine with electrons arriving from the external charging circuit through the gel's electronic conductivity network to form metal-hydrogen surface bonds. Charging is terminated when the cell reaches its target state of charge, at which point the bias is removed and the cell relaxes to the equipotential storage state.

In the storage state, the gel is at uniform potential throughout. The metal-hydrogen bonds are stable: the bonding electrons remain in place, the surrounding hydrophobic regions prevent neutral-hydrogen escape, the like-charged particle repulsion prevents cross-particle recombination, and the absence of an internal potential gradient prevents internal current redistribution. Self-discharge mechanisms characteristic of conventional rechargeable cells — electrolyte decomposition, SEI growth, transition-metal dissolution — are absent from the disclosed architecture. Calendar-life self-discharge is projected to be substantially below conventional cells; quantitative ranges await empirical determination.

Discharge is initiated by closure of an external circuit through a load. The external load creates an asymmetric path for electrons, establishing a potential gradient across the gel. Electrons drain from metal-hydrogen bonds at particles near the exit terminal first, with the drain proceeding through the gel's electronic conductivity network. As electrons drain, the corresponding metal-hydrogen bonds destabilize and release the hydrogen as cold protons into the hydrophilic channels. The cold protons migrate through the channels to the entry terminal under the discharge-direction gradient, where they recombine with electrons returning through the external circuit. Discharge continues at a rate set by the load impedance until the cell reaches its lower state-of-charge limit or the load is opened.

9. Open Empirical Questions

The mechanism-level design described above is grounded in published materials science at every component, but the integration is novel and the practical performance must be established empirically. The following is the honest list of empirical questions that prototype testing must answer, ordered by consequence.

The first question is the stability of surface hydrogen at engineering-relevant timescales. Surface-bonded hydrogen on aluminum has been characterized in ultrahigh-vacuum surface-science studies at minutes-to-hours timescales. The stability of the same bonds within the disclosed gel environment — across hours, days, and years — has not been empirically determined. The mechanism admits long-term stability, but only prototype testing can establish the actual half-life of the bonded state at engineering-relevant conditions.

The second question is the synthesizability of the dual-domain gel structure with metal nanoparticles selectively distributed in the hydrophobic domain. Each constituent — the carbon framework, the sulfonate functionalization, the hydrophobic functionalization, the metal nanoparticle dispersion — has prior art individually. The integrated phase-separated structure with selective particle placement is a synthesis challenge that will require methodological development.

The third question is realistic cycle life and round-trip efficiency. Cycle life and round-trip efficiency are determined by the rates of mechanical fatigue at particle surfaces, the rate of side-reaction accumulation in the gel, and the kinetic overpotentials at both terminals. The mechanism admits long cycle life by construction — there is no transition-metal dissolution, no SEI formation, no dendrite mechanism, no aluminum oxidation in the absence of oxygen ingress — but the actual cycle life will depend on engineering details only prototype data can settle. Round-trip efficiency is projected in the 80 to 90 percent range based on mechanism-level kinetic considerations; experimental verification awaits.

The fourth question is manufacturing tolerance and yield. The economic viability of the disclosed cell at industrial scale depends on the manufacturing tolerance of the gel synthesis, the yield of the metal-particle dispersion, and the consistency of the phase-separation morphology. We have not established these quantitatively; we have established that the synthesis is achievable with conventional sol-gel and electrochemical-deposition techniques.

None of these open questions implies that the architecture will not work. They are quantitative questions about the magnitude of effects, not fundamental questions about whether the architecture is buildable. Each is tractable on prototype-testing timescales.

10. Conclusion and Disclosure Scope

We have described a sealed electrochemical cell architecture that stores energy as electron-mediated hydrogen-aluminum surface bonds in a continuous proton-conducting carbon gel, with charge retained by bulk-equipotential saturation rather than by an internal separator. The mechanism-level design yields a projected cell-level energy density in the 200 to 500 watt-hours per kilogram range, competitive with the upper edge of commercial lithium-ion and the aspirational envelope of next-generation lithium-metal cells. The architecture eliminates several of lithium-ion's principal engineering and safety constraints:

no flammable organic electrolyte, no internal separator to fail, no supply-constrained materials, and a benign breach-response chemistry.

The component-level mechanisms are all grounded in published materials science. The integrated combination is, to our knowledge, novel. The architecture is buildable from existing materials at near-ambient conditions, and the central empirical questions are tractable through conventional prototype testing on the timescale of months.

This article discloses the foundational architecture and the mechanism-level operating principles sufficient to support experimental replication. It does not disclose the synthesis-route specifics for the dual-domain gel, the additive selection that admits full operational performance, the conditioning protocols that establish the steady-state operating envelope, or several architectural enhancements that are retained as trade secret. These are the subject of separate patent filings and will be disclosed progressively as the inventive position matures and as commercial partnerships warrant. The disclosed scope is what we believe is sufficient to demonstrate the architecture's experimental credibility, to invite serious technical engagement, and to publish openly without exhausting the inventive content.