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Boron Doping of the Carbon Framework as a Multi-Function Precision Multiplier

Boron doping of the carbon framework as a precision multiplier is a secondary inventive step of the Hydrogen-Aluminum Energy Cell disclosed in U.S. Provisional Application No. 64/055,649. Carbon is a structurally promiscuous host: its sp2 and sp3 bonding admits a wide dispersion of geometries, and the placement of defects, edges, and dopant sites is only loosely controllable through synthesis. For a hydrogen-aluminum surface-bond cell whose performance depends on a precisely structured dual-domain proton-conducting gel, that geometric variety is a liability. The filed specification discloses substitutional and interstitial boron doping of the gel carbon framework as a single intervention that constrains that geometry. Through three-center two-electron bonding and preferential icosahedral and planar cluster motifs, boron imposes geometric precision on the surrounding carbon, and that precision propagates into several otherwise separate cell functions at once: sharper hydrophilic-hydrophobic domain boundaries, higher specific surface area, boron-mediated proton hopping, and tunable bulk electronic conductivity. The disclosure frames this as a precision multiplier, a cumulative effect across substantially all operating mechanisms rather than a single tuned parameter.

The Problem: Carbon's Loose Geometry

The disclosed cell stores energy in metal-hydrogen surface bonds across a continuous conductive gel, and the gel's carbon framework is asked to do several distinct jobs at once: carry the dual-domain structure that separates hydrophilic Grotthuss proton paths from hydrophobic gating regions, present enough surface area to host hydrogen-binding sites, conduct protons through its hydrophilic channels, and conduct electrons well enough to support the bulk-equipotential charge retention principle. The specification identifies a structural obstacle to all of these jobs. Carbon's natural geometric variety is limited to sp2 trigonal-planar and sp3 tetrahedral configurations, but the transition between them and the precise placement of defects, edges, and dopant sites is only loosely controllable through synthesis. The result is a wide dispersion of geometric configurations across the gel volume, which blurs every feature the cell depends on.

Boron's Geometric Constraint

The specification's central claim for boron is geometric, not chemical. Boron's electron-deficient bonding, including the formation of three-center two-electron bonds and the preferential formation of well-defined icosahedral and planar cluster motifs, imposes geometric precision on the surrounding carbon framework. That precision admits sharper definition of structural features at the nanometer and sub-nanometer scale and reduces the dispersion of geometric configurations across the gel volume. The carbon framework of the dual-domain proton-conducting gel is disclosed as admitting both substitutional doping (boron replacing carbon atoms in the lattice) and interstitial doping (boron between carbon planes), along with edge-site and domain-boundary boron. Because the same geometric constraint sharpens many features, one doping intervention reaches multiple functions. The specification names this the precision multiplier: the cumulative effect of boron doping across multiple operating mechanisms, expressed as capacity multipliers, performance multipliers, and efficiency multipliers over analogous undoped embodiments.

Concentration and Site Distribution

The disclosed boron concentration is in the range of approximately 0.5 to 15 atomic percent of total framework atoms, with preferred ranges of approximately 2 to 5 atomic percent for basic engineering implementations and approximately 8 to 12 atomic percent for high-density mature engineering implementations. The specification also discloses deliberately non-uniform distribution: locally elevated concentrations at hydrophilic-hydrophobic domain boundaries (approximately 5 to 25 atomic percent), at flake-gel interface regions (approximately 3 to 12 atomic percent), and within the auxiliary carbon reservoir (approximately 2 to 10 atomic percent). That non-uniform distribution admits site-specific tuning of the gel's behavior and is achieved through synthesis routes including co-deposition of boron and carbon precursors, post-synthesis boron infiltration of pre-formed carbon gels, and gradient-doping techniques. The boron is incorporated at substitutional sites, interstitial sites, edge sites on graphenic regions, and at the boundaries between hydrophilic and hydrophobic domains, and the concentration ranges are selected to admit the site populations those downstream effects require.

Sharper Domain Boundaries Improve Gating

Boron doping placed at the hydrophilic-hydrophobic domain boundaries admits sharper definition of those boundaries than undoped embodiments achieve. The specification ties this directly to the cell's asymmetric kinetic gating function: sharper boundaries admit cleaner discrimination between hot and thermalized proton species, so 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. The disclosed consequence is charging at lower applied voltages, approximately 1.4 to 2.0 volts versus approximately 1.8 to 2.5 volts in undoped embodiments, together with reduced self-discharge rates at extended storage durations.

Higher Specific Surface Area

The geometric precision imposed by boron also raises the gel's specific surface area. The specification attributes the increase to finer pore networks, longer hydrophilic channels with smaller channel cross-sections, more uniform hydrophobic domain morphologies, and higher exposed-edge fractions in graphenic regions. Typical specific surface area values for the boron-doped framework are in the range of approximately 1,500 to 3,500 square meters per gram, compared to approximately 500 to 1,200 square meters per gram for analogous undoped frameworks at equivalent processing conditions. The disclosure states that this surface area increase translates directly into proportional increases in proton transport capacity, ion-electrolyte interfacial area, and accessible reaction sites at the flake-gel interface. Because hydrogen-binding sites scale with surface area, this effect is identified as a principal source of the capacity multiplier.

Boron-Mediated Proton Hopping

Within the hydrophilic channels, the boron sites function as proton-hopping waypoints that accelerate Grotthuss-mechanism proton conduction. The specification attributes the acceleration to the electron-deficient character of boron sites, which admits transient proton localization at the site followed by rapid release upon hop completion. Effective proton conductivity in the boron-doped hydrophilic channels is in the range of approximately 0.10 to 0.40 siemens per centimeter, compared to approximately 0.05 to 0.20 siemens per centimeter in undoped embodiments. The disclosed downstream effects are higher discharge current rates, lower internal resistance, and improved high-rate performance. Alongside the surface-area enhancement, this proton-mobility enhancement is identified as a principal contributor to the disclosed capacity multiplier, which is stated as approximately 1.15 to 1.35x over analogous undoped capacity for basic engineering implementations, with stretch values up to approximately 1.4 to 1.5 for mature engineering implementations at higher boron concentrations and optimized site-specific distributions.

Tunable Bulk Electronic Conductivity

Boron is disclosed as the standard p-type dopant for carbon-based electronic materials, and the specification uses concentration as the control knob for the bulk gel's electronic conductivity. By controlling boron concentration, that conductivity may be tuned across the range of approximately 0.1 to 200 siemens per centimeter, with the range admitting selection of values optimized for current collection at the cell's operating current densities while remaining compatible with the bulk-equipotential charge retention principle. Higher boron concentrations admit higher electronic conductivity for high-rate applications; lower concentrations admit reduced conductivity for applications prioritizing minimal parasitic-path losses. The specification also frames boron as chemically conservative: boron-hydrogen bonds require coordination geometries not achieved at substitutional or interstitial boron sites in graphenic frameworks under the cell's operating conditions, and boron-metal bonding with active metals is not thermodynamically favored at the cell's operating temperatures. Boron therefore modifies how the carbon behaves without entering the storage chemistry.

Doping the Mobile Carbon and Locking Boron During Synthesis

The precision multiplier extends to the auxiliary carbon reservoir, which may include a fraction of boron-doped mobile carbon species alongside undoped mobile carbon. During mechanochemical healing, the boron-doped mobile carbon migrates to mechanically strained sites in the metal nanoflakes and forms boron-carbon bonds that exhibit higher bond strength and higher mechanical stiffness than carbon-carbon bonds, a property the specification attributes to published research on boron-carbon composite mechanics. This is disclosed as a modest, empirically-to-be-determined cycle-life effect, with estimated ranges of approximately 8,000 to 40,000 deep-discharge cycles for boron-doped embodiments versus approximately 5,000 to 30,000 cycles for analogous undoped embodiments, and is explicitly secondary to the surface-area and proton-mobility effects. On the synthesis side, the framework is produced by dosing biomass feedstock with a boron precursor (boric acid, boron oxide, borax, trimethyl borate, or analogous compounds) before a static-electrostatic reduction step. The applied DC field during reduction locks boron incorporation at electrostatically determined sites, so the disclosed boron placement is established at synthesis rather than left to migrate. The specification also recites a long-timescale degradation mode in which mobile aluminum cations migrate to boron sites and competitively displace boron-carbon bonding character, progressively degrading the precision multiplier, with mitigations and an order-of-magnitude half-life estimate of approximately 30 to 200 years at typical operating conditions.

Disclosure Scope

This article describes subject matter disclosed in U.S. Provisional Application No. 64/055,649. The boron concentrations, distributions, surface area values, proton and electronic conductivity ranges, voltage figures, cycle-life ranges, capacity multipliers, and timescale estimates stated above are those recited in the filed specification, which characterizes the cell as an early-stage disclosure of concepts and mechanisms. No numerical value, material property, or mechanism beyond what the specification recites is asserted here, and prophetic and to-be-determined figures are identified as such in the underlying disclosure.

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)