

PVD for Solid State Lithium-Ion Batteries in Space Applications

Spacecraft power systems operate under constraints that eliminate many conventional energy storage options. CubeSats and small satellites in low Earth orbit experience thermal excursions from -20°C to $+60^{\circ}\text{C}$ or wider, sustained exposure to ionising radiation, and hard mass and volume limits, with no option for in-orbit maintenance or electrolyte replacement.^[1] Commercial lithium-ion cells used in most current small satellite missions were not designed for these conditions: liquid electrolyte batteries carry inherent leakage risk, electrolyte decomposition accelerates under radiation, and cell-level packaging adds mass and volume that constrains instrument payload capacity.

Thin-film all-solid-state lithium-ion batteries fabricated by physical vapour deposition (PVD) address each of these constraints. Sequential vacuum deposition of cathode, solid electrolyte, and anode layers produces monolithic battery stacks with no liquid phase, nanometre-scale thickness control, and dense microstructures with strong substrate adhesion.^{[2],[3]} RF magnetron sputtering is the dominant PVD technique for this application, primarily for deposition of lithium phosphorus oxynitride (LiPON) solid electrolyte and LiCoO_2 cathode thin films. This blog examines the materials, deposition methods, documented performance data, and key fabrication parameters relevant to PVD-based thin-film batteries for space use.

Space Requirements and the Case for Thin-Film Solid-State Batteries

Most small satellite programmes rely on commercial off-the-shelf lithium-ion cells that must be individually qualified against radiation exposure, thermal cycling range, and launch safety requirements.^[4] Thin-film solid-state batteries fabricated by PVD offer a structurally distinct solution: all-solid-state construction removes the leakage risk associated with liquid electrolytes; vacuum-deposited dense films maintain structural integrity under mechanical vibration and thermal shock during launch and orbital cycling; and the planar, thin geometry of PVD battery stacks enables direct integration with spacecraft printed circuit boards, eliminating the separate battery module housings that add mass to small satellite platforms.

The long-cycle durability of Li/LiPON/LiCoO₂ thin-film batteries was established in foundational work at Oak Ridge National Laboratory, where PVD-deposited cells demonstrated over 30,000 charge-discharge cycles with less than 5% capacity fading.^[4] That cycling endurance is directly relevant to low-Earth-orbit missions, where batteries complete approximately 15 charge-discharge cycles per day over a multi-year mission lifetime. Thin-film batteries are also applicable to planetary surface instrumentation, CMOS backup power in satellite avionics, and structural power integration in CubeSat panels where mass and form factor are primary constraints.

Why RF Magnetron Sputtering is the Preferred Thin-Film Battery Deposition Method

PVD encompasses thermal evaporation, electron beam evaporation, pulsed laser deposition, and magnetron sputtering. For thin-film solid-state lithium-ion batteries, RF magnetron sputtering is the most widely adopted technique because it operates across both conductive and insulating target materials via RF excitation at 13.56 MHz, delivering particle energies of 10–40 eV that produce dense, well-adhered films, and supports working pressures of 0.1–10 Pa compatible with reactive sputtering in nitrogen and oxygen atmospheres. ^[5]

Multi-target sputtering systems allow cathode, electrolyte, and anode layers to be deposited sequentially in a single vacuum run, which is critical for interface quality: atmospheric exposure between deposition steps introduces surface contamination that increases interfacial resistance in the completed cell. ^[2] Reactive sputtering of Li_3PO_4 in pure N_2 converts the target material directly to amorphous LiPON electrolyte at room temperature, eliminating the high-temperature processing that would structurally damage previously deposited electrode layers. ^[4] These characteristics make RF magnetron sputtering the preferred route for sequential thin-film battery stack fabrication.

PVD-Deposited Cathode, Electrolyte, and Anode Materials for Space Batteries

LiCoO_2 (LCO) is the most extensively characterised RF magnetron sputtered cathode for thin-film solid-state batteries. Sputtering from LCO targets in Ar/O_2 (3:1) atmospheres, followed by post-deposition annealing at 600–700°C, produces films with (104)-preferred crystallographic orientation that supports fast Li^+ diffusion kinetics. Capacity fading of 0.0001% per cycle at $100 \mu\text{A cm}^{-2}$ has been documented for 50 nm thick films, and 0.002% per cycle for 500 nm films, over 10^4 cycles. ^[5] LCO/LiPON/Li microcells on flexible mica substrates have demonstrated 10C rate capability with 95% capacity retention over 800 cycles. ^[5]

LiPON solid electrolyte, deposited by RF sputtering of a Li_3PO_4 target in pure N_2 , is amorphous, electrochemically stable from 0 to 5.5 V vs. Li^+/Li at room temperature, and chemically stable in contact with lithium metal. Typical ionic conductivity is $2\text{--}3 \times 10^{-6} \text{ S cm}^{-1}$ at 25°C. ^[4] Ti-LiPON prepared by multi-target co-sputtering of Li_3PO_4 and Ti in N_2 atmosphere achieved an ionic conductivity of $4.91 \times 10^{-6} \text{ S cm}^{-1}$ and a stability window above 5.5 V, with a $\text{LiCoO}_2/\text{Ti-LiPON}/\text{Ni}$ full cell showing 67% capacity retention after 50 cycles. ^[6] Carbon-doped Li_3PO_4 targets, which convert the normally insulating Li_3PO_4 to a conductive target compatible with DC sputtering, increase LiPON deposition rates by a factor of four to ten over standard undoped targets; a 300 nm LiPON layer from this route showed negligible degradation after 190 cycles in a Li-metal thin-film cell. ^[7]

For thin-film anodes, silicon-based films deposited by magnetron sputtering offer a high theoretical specific capacity of 3579 mAh g^{-1} for $\text{Li}_{15}\text{Si}_4$. Amorphous Si films of 1 μm thickness deposited on graphite by HiPIMS (high-impulse-power magnetron sputtering) delivered an initial discharge capacity of 628.7 mAh g^{-1} , 96.2% capacity retention at C/3, and 250 mAh g^{-1}

at 3C. ^[8] Co-sputtering of Si with Li₂O to form a composite anode reduced volume expansion effects through pre-lithiation and in-situ protective layer formation: the composite delivered 2357 mAh g⁻¹ initial specific capacity and 88.4% retention after 100 cycles at 0.5C, compared with 60.7% for a pure Si film under the same conditions. ^[9]

Critical Deposition Challenges for PVD Thin-Film Batteries

1. **Lithium loss during sputtering:** Lithium has a high vapour pressure and selectively re-evaporates from the substrate during deposition, producing Li-deficient films with reduced ionic conductivity. Compensation strategies include Li-enriched sputtering targets and Li₂O co-sputtering. Reliable stoichiometry across deposition runs requires tight control of gas composition, substrate temperature, and RF power density. ^[2] ^[4]
2. **Plasma-induced interfacial damage:** During LiPON electrolyte deposition over a pre-deposited LCO cathode, energetic ions from the sputter plasma bombard the cathode surface. Substrate bias potential relative to the cathode potential propagated through the plasma is the primary control parameter: uncontrolled bias causes interfacial resistance to increase. Chemical reactions at the LiCoO₂/LiPON interface during electrochemical cycling producing oxidised cobalt species and lithium oxide/peroxide are an additional source of impedance growth that is independent of the deposition process. ^[2] ^[10]
3. **Silicon anode volume expansion:** Si anodes expand volumetrically by up to 400% on full lithiation. The resulting internal stress causes cracking, delamination from the current collector, and progressive capacity fading. Compositionally graded SiCu thin films deposited by magnetron co-sputtering with a Cu-rich interfacial layer for adhesion and a graded composition to distribute stress retained 600 mAh g⁻¹ after 100 cycles at 99.9% Coulombic efficiency, whereas non-graded SiCu films of equivalent composition degraded rapidly over the same period. ^[11]
4. **Crystallisation and annealing sequencing:** LCO films require annealing at 600–700°C to achieve the (104)-oriented layered structure needed for high Li⁺ diffusion rates. Applied after electrolyte deposition, this thermal step would decompose LiPON; the annealing step must therefore precede electrolyte deposition. The thermal treatment also drives Li diffusion into adjacent layers and generates mechanical stress from differential thermal expansion between film and substrate, requiring substrate and stack architecture to be selected with the annealing sequence in mind. ^[2] ^[5]
5. **Low LiPON deposition rate from standard targets:** Standard RF sputtering of insulating Li₃PO₄ in N₂ is slow, making thick electrolyte layers time costly. Carbon-doped Li₃PO₄ targets increase deposition rate four to ten-fold in both RF and DC modes without introducing measurable carbon contamination in the deposited LiPON film, as confirmed by XPS. The resulting films exhibit ionic conductivity of 2–5 × 10⁻⁷ S cm⁻¹, improvable by Li₂O co-sputtering, and a 300 nm layer integrated in a Li-metal cell showed negligible degradation after 190 cycles. ^[7]

Recent Progress in Sputtered Thin-Film Batteries

Deposited two LCO/LiPON/Si cells monolithically in a single vacuum stack, with LCO at 300 nm (RF sputtered in Ar/O₂ at 15.3 W cm⁻²) and LiPON at 800 nm (RF sputtered in N₂ at 5.1 W cm⁻²). The stacked cell cycled for over 300 cycles between 6 and 8 V. Thermoelectric modelling of the architecture predicted specific energies above 250 Wh kg⁻¹ at C-rates above 60, with specific powers in the tens of kW kg⁻¹.^[3] A fully magnetron-sputtered Ti/ZnO/LiPON/LiMn₂O₄/Ti cell fabricated on glass without any post-deposition heat treatment delivered a stable reversible capacity of 22 μAh cm⁻² between 0.5 and 5 V at 5 μA cm⁻². The absence of a thermal annealing requirement makes this architecture relevant to temperature-sensitive spacecraft substrates. All-solid-state thin-film Li-S batteries prepared by RF magnetron sputtering of a VGs-Li₂S cathode with LiPON electrolyte completed more than 3,000 cycles with stable performance at temperatures up to 60°C, within the upper range of low-Earth-orbit thermal cycling conditions.^[12]

On electrolyte development, Mn-doped LiPON prepared by multi-target co-sputtering delivered enhanced ionic conductivity compared with undoped LiPON in otherwise identical thin-film cell architectures, with documented improvement in full-cell electrochemical performance.^[13] These results demonstrate that multi-target RF magnetron sputtering is both the current production standard for LiPON-based batteries and the active platform for next-generation electrolyte and electrode compositional development.

Key Deposition Parameters for Thin-Film Battery Fabrication

- Substrate selection and surface preparation:** Current collectors deposited by DC sputtering on flat substrates Pt is the standard reference material; Al has been used for mass-critical applications provide the conductive, smooth base layer for subsequent LCO cathode deposition. Substrate crystallographic orientation influences LCO texture: c-plane sapphire and Si(100) with appropriate buffer layers support (104)-oriented LCO growth and faster Li⁺ diffusion. Surface cleaning before each deposition step is essential to avoid contamination-driven interfacial resistance.^[5]
- Gas composition and working pressure:** LiPON deposition uses pure N₂ at 0.3–1 Pa. LCO cathode sputtering uses Ar/O₂ at approximately 3:1 ratio to maintain near-stoichiometric oxide composition. Working pressure determines the mean free path of sputtered species and their kinetic energy at the substrate: lower pressures increase film density but elevate compressive stress. Each target-substrate combination requires pressure optimisation to balance density against stress-induced delamination risk.^{[2] [4]}
- RF power density and multi-target configuration:** LCO is typically sputtered at 2–3 W cm⁻² RF power density. Multi-target systems that enable sequential or simultaneous co-sputtering within a single pump-down cycle are strongly preferred over single-target systems: they preserve interface quality, permit in-situ stoichiometry compensation for lithium loss, and reduce total process time. Carbon-doped Li₃PO₄

targets enable DC sputtering of LiPON at four to ten times the deposition rate of standard RF sputtering from insulating targets. [7]

4. **Annealing sequence and temperature control:** LCO films require 600–700°C annealing to crystallise into the electrochemically active R-3m layered structure. Annealing is performed after cathode deposition and before electrolyte deposition to prevent thermal decomposition of LiPON. Where substrate temperature limits preclude high-temperature annealing, amorphous LiMn_2O_4 cathode films deposited without heat treatment have demonstrated functional capacity in fully sputtered cell stacks, providing a route to battery fabrication on lower-temperature spacecraft substrates. [12]

Why Choose Nikalyte for PVD Thin-Film Battery Development

Nikalyte's [NEXUS](#) ultra-high vacuum [PVD system](#) operates at base pressures down to 5×10^{-7} Torr, providing the contamination-free deposition environment required for high-purity LiPON electrolyte and LCO cathode films. Substrate heating to 800°C supports LCO crystallisation within the same vacuum environment, eliminating atmospheric exposure between cathode deposition and thermal annealing and preserving interface quality in the completed stack. [15]

The [Tri-Stellar](#) triple-target sputter source enables multi-target co-sputtering the configuration used in peer-reviewed work on Ti-doped LiPON, Mn-doped LiPON, and Si/Li₂O composite anodes, within a single vacuum run. Stellar magnetron sputter sources support both DC and RF operation, accommodating the full range of thin-film battery target materials: conductive current collector metals (Pt, Al, Ti) by DC sputtering and insulating LiPON targets by RF sputtering. Bakeable UHV-compatible designs maintain base pressure stability across the extended sequential deposition runs required for multi-layer battery stacks. [15]

Conclusion

RF magnetron sputtering is the established fabrication method for thin-film all-solid-state lithium-ion batteries with the performance characteristics required for space applications: no liquid electrolyte, layer-by-layer vacuum deposition with controlled interfaces, and long cycle life documented at over 30,000 cycles with less than 5% capacity fading. Recent peer-reviewed work has confirmed monolithically stacked thin-film cells at specific energies above 250 Wh kg^{-1} at high C-rates, LiPON deposition rate increases of four to ten times via carbon-doped targets, and thin-film cell operation to 3,000+ cycles at temperatures up to 60°C. Multi-target co-sputtering systems that enable sequential deposition of cathode, electrolyte, and anode within a single vacuum run are the practical platform for both research-scale cell development and transition towards integrated spacecraft power systems.

[Contact us](#) to discuss how the [NEXUS](#) system and Nikalyte's [sputter](#) sources can support your thin-film solid-state battery development programme

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