

## **Fabrication, Testing and Simulation of All Solid State Three Dimensional Li-ion Batteries**

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Demonstration of 3-dimensional all-solid state Li-ion batteries (3D SSLIBs) has been a long standing goal for numerous researchers in the battery community interested in developing high power and high areal energy density storage solutions for variety of applications. Ideally, the 3D geometry maximizes the volume of active material per unit area, while keeping its thickness small to allow for fast Li diffusion. In this paper we describe experimental testing and simulation of 3D SSLIBs fabricated using materials and thin film deposition methods compatible with semiconductor device processing. These 3D SSLIBs consist of Si microcolumns onto which the battery layers are sequentially deposited using physical vapor deposition (PVD). The power performance of the 3D SSLIBs lags significantly behind that of similarly prepared planar SSLIBs. Analysis of the experimental results using finite element modeling indicates that the origin of the poor power performance is the structural inhomogeneity of the 3D SSLIB, coupled with low electrolyte ionic conductivity and diffusion rate in the cathode, which lead to highly non-uniform internal current density distribution and poor cathode utilization.

## I. Introduction

Realization of safe, long cycle life and simple to package solid-state rechargeable batteries with high energy and power density has been a long-standing goal of the energy storage community.<sup>1-3</sup> Much of the research activity has been focused on developing new solid electrolytes with high Li ionic conductivity. Indeed, LiPON, the only solid electrolyte currently used in commercial thin film solid state Li-ion batteries (SSLIBs), has a conductivity of  $\approx 10^{-6}$  S/cm, compared to  $\approx 0.01$  S/cm typically observed for liquid organic electrolytes.<sup>4</sup> Replacing LiPON with a solid electrolyte such as LiLaTaO<sub>3</sub> or LiGeSP with ionic conductivity of  $\approx 10^{-3}$  S/cm to  $10^{-2}$  S/cm, however, may not improve significantly the power performance of thin film SSLIBs due to the sluggish Li diffusion in the cathode. For example, in LiCoO<sub>2</sub> based thin-film SSLIBs with LiPON electrolyte the diffusion of Li<sup>+</sup> in the cathode becomes the rate limiting step for cathode thickness exceeding  $\approx 1$   $\mu\text{m}$ .<sup>5</sup> Decreasing the cathode layer significantly below 1  $\mu\text{m}$  is impractical for the thin-film battery since this further reduces the areal charge density from the already low value of  $\approx 0.1$  mAh/cm<sup>2</sup>. In order to decouple the power density from energy density, numerous proposals have been made to replace the planar, two-dimensional (2D) substrate of the thin film SSLIB with a 3D scaffolding onto which the battery layers are sequentially deposited.<sup>6</sup> The various proposed 3D SSLIB designs use height (vertical topology) to increase both the electrode surface area and the energy density per geometric footprint. An advantage of the 3D approach is that the anode and cathode sub-structures can be arranged in close proximity, so that the Li<sup>+</sup> diffusion length during cycling remains short. Furthermore, the increased electrode/electrolyte interfacial area reduces local current density, which in turn leads to lower charge transfer overpotential. Indeed, there are numerous reports of 3D structured electrodes combined with liquid electrolytes that clearly demonstrate the advantages of reduced

diffusion length and high interfacial area for high power performance.<sup>2,7-8</sup> However, extending these designs into complete 3D SSLIB with solid electrolytes and with competitive performance characteristics has so far eluded researchers.

In this paper we demonstrate structural and electrochemical characterization of 3D SSLIBs fabricated using materials and thin film deposition methods compatible with semiconductor device processing. We use numerical modeling to relate the structure and performance of the 3D SSLIBs and draw conclusions useful for continued development of high power and high energy density solid state energy storage devices. Our 3D SSLIBs consist of conical or cylindrical Si microcolumns onto which layers corresponding to the current collector, cathode, electrolyte and anode, are sequentially deposited using physical vapor deposition (PVD). Using galvanostatic charge/discharge cycling, we demonstrate that the power performance of the 3D SSLIBs lags significantly behind that of similarly prepared planar SSLIBs. Analysis of the experimental results using finite element modeling indicates that the origin of the poor power performance is the structural inhomogeneity of the 3D SSLIB, coupled with low electrolyte ionic conductivity, which lead to highly non-uniform internal current density distribution and poor cathode utilization. Our results further confirm that structural uniformity is essential for optimum 3D SSLIB performance and that the existing PVD processes appropriate for planar geometry SSLIBs will likely have to be replaced by alternate processes capable of uniformly coating high aspect ratio microstructures. Based on our analysis we derive a quantitative relationship between the structural inhomogeneity and capacity for different solid electrolyte conductivity values and which can be applied, at least semi-quantitatively to a variety of SSLIB and composite electrode designs.

## **II. Experimental**

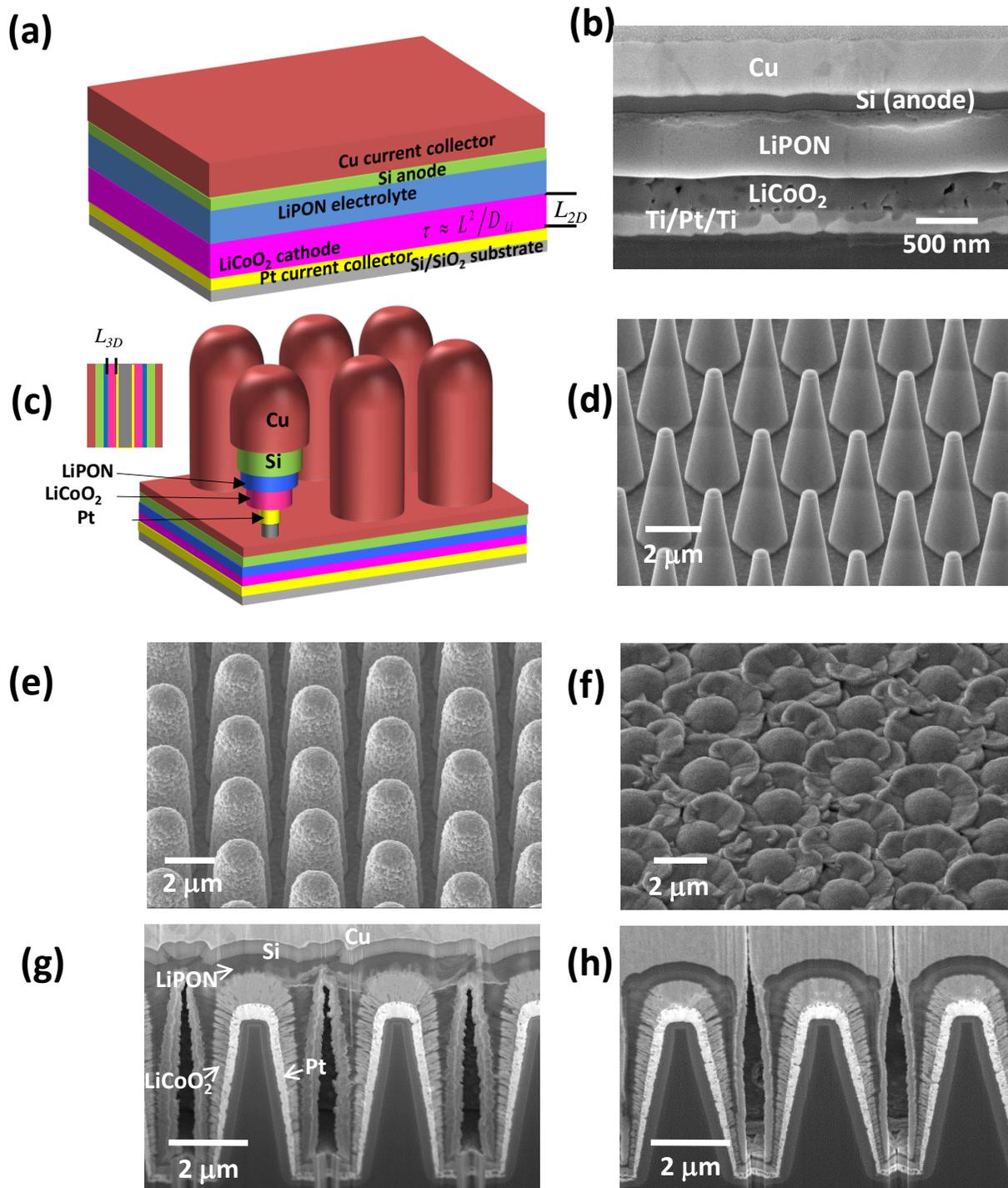
The fabrication process for the planar (2D) batteries has been previously described.<sup>9</sup> Briefly, the process was begun by coating Si (001) substrates capped with 100 nm thick thermal SiO<sub>2</sub> with Ti/Pt (20 nm/120 nm), which serves as the cathode current collector. LiCoO<sub>2</sub> (nominal thickness ≈300 nm) is then deposited by sputtering in the same system. The samples were then annealed in ambient oxygen at 700 °C for 2 h to form the LiCoO<sub>2</sub> high-temperature (HT) phase as determined by Raman spectroscopy.<sup>10</sup> The samples were next sputter-coated with ≈500 nm of LiPON electrolyte at substrate temperature of 200 °C. The final step consisted of deposition of ≈100 nm of Si followed by ≈400 nm of Cu current collector using a stainless steel shadow mask with an array of 0.5 mm diameter holes to define individual ‘microbatteries’ (see Fig. S1a).

The 3D SSLIBs were fabricated using the same procedure on substrates that consisted of arrays of conical Si microcolumns coated with ≈300 nm of SiO<sub>2</sub> (see Supporting Information for additional fabrication details). The Si conical microcolumns measured 4 μm in height, 1.6 μm diameter at the base, and were positioned with pitch of 3.6 μm. A Si substrate with cylindrical microcolumns was also used for fabricating similar 3D SSLIB and is shown along with galvanostatic charge/discharge data in Supporting Information.

The planar SSLIBs were tested using a micromanipulator probe station placed inside an Ar-filled glovebox. The 3D SSLIBs were tested using a custom scanning electron microscope equipped with an electrical micromanipulator probe in order to avoid damaging the microcolumn arrays.<sup>11-12</sup> The testing included galvanostatic charge/discharge cycling at current densities ranging from 2 μA/cm<sup>2</sup> to 70 μA/cm<sup>2</sup> and cyclic voltammetry (CV) carried out from 0 V to 4 V at a rate of 0.1 mV/s. Additional planar specimens were prepared specifically for EIS measurements, consisting of a planar SSLIB with LiCoO<sub>2</sub> thickness of 200 nm, LiPON thickness

of 580 nm and Si thickness of 50 nm; a companion specimen consisting of 580 nm of LiPON sandwiched between two Au contacts (the LiPON deposited at the same time as the battery) was also fabricated. Electrochemical impedance spectroscopy (EIS) measurements were made using a commercial potentiostat rated for  $\mu\text{V}$  and fA precision in sourcing/measuring voltage and current, respectively, with the AC signal frequency varied from 1 Hz to 1 MHz with amplitude of 25 mV. Note that all deposited layer thicknesses were determined using scanning electron microscopy (SEM) on focused ion beam (FIB) prepared cross sections. The uncertainty (one standard deviation) in the dimensions and thicknesses is estimated to be  $\approx 5\%$  of the value for the planar batteries and  $\approx 10\%$  for the 3D batteries. The electrochemical charge/discharge cycling was performed with high precision instrumentation with 1 fA current sourcing resolution, 1 mV voltage (potential) resolution and 1 s time resolution, which translated into an accuracy of  $\pm 0.02 \text{ mAh/cm}^2$  for charge capacity determination. Nevertheless, because too few planar and 3DSSLIBs were measured in this study to calculate standard deviations, the reported capacities are preceded with the “ $\approx$ ” symbol to indicate that these are approximate values, and that we are mainly concerned with demonstrating and understanding the difference in the capacity measured at different charge rates between the planar and 3D structured solid state batteries.

Finite element simulations describing the time-dependent non-uniform distributions of  $\text{Li}^+$  and the electric potential were used to compute charge and discharge curves for a 3D SSLIB based on the experimental input. Simulations were performed on a desktop PC using a commercial finite element program and are detailed in Supporting Information.



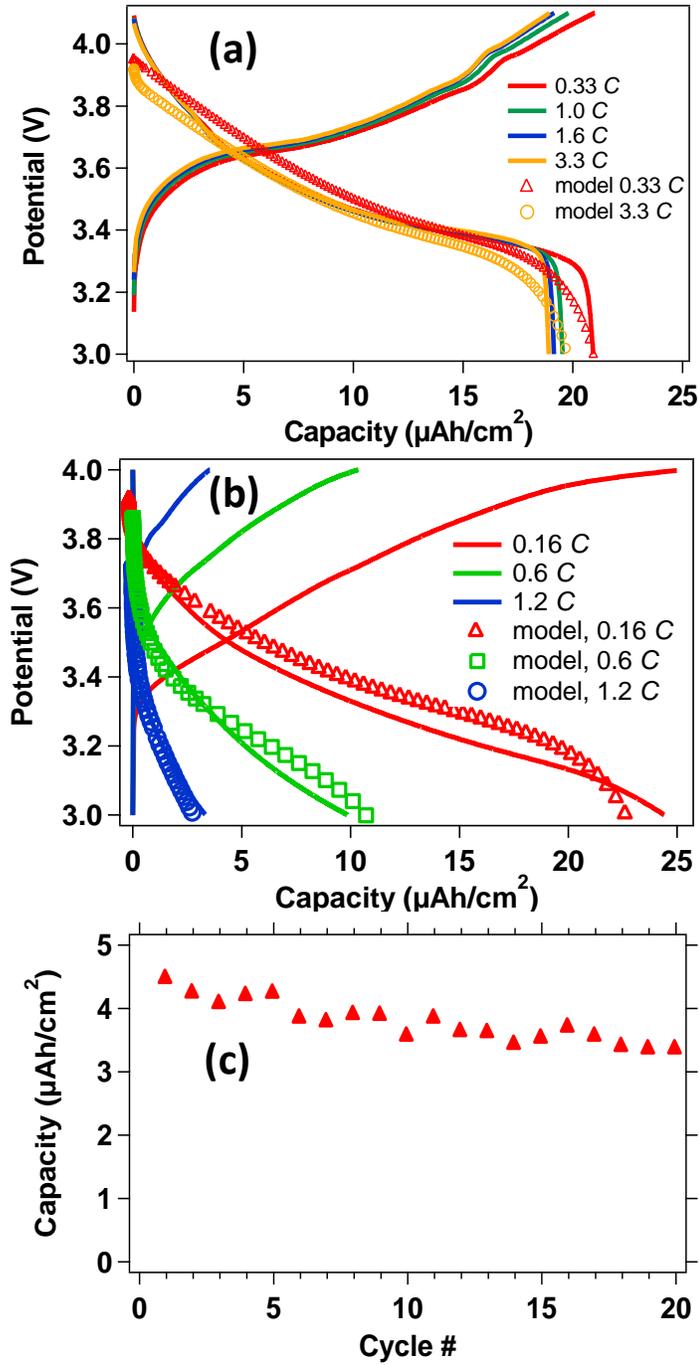
**Figure 1.** (a) Schematic of a planar thin film SSLIB. (b) Focused ion beam cross section of a thin film SSLIB. (c) Schematic of a 3D SSLIB. (d) Si conical microcolumns used as scaffolding for 3D SSLIB. (e) following Ti/Pt and LiCoO<sub>2</sub> deposition. (f) following Si and Cu current collector deposition. (g), (h) FIB cross sections of 3D SSLIBs with nominally 500 nm and 250 nm thick LiPON, respectively.

### III. Results and Discussion

A schematic of the planar SSLIB and a representative SEM image of a cross section prepared using a focused ion beam (FIB) are shown in Figs. 1a and 1b, respectively. A schematic of an idealized 3D SSLIB along with a sequence of three SEM images collected at different stages of fabrication ( $\text{SiO}_2$  coated microcolumn array,  $\text{LiCoO}_2$  deposition, anode deposition) are shown in Figs 1c – 1f; a FIB prepared cross section of a completed 3D SSLIB is shown in Fig. 1g. Additional images for similarly prepared 3D SSLIBs are shown in Supporting Information. Although the various layers seen in the cross section in Figure 1 were not chemically identified in this study, we previously used multimode analytical scanning/transmission electron microscopy imaging and tomography to characterize in detail the various layers in similarly prepared isolated nanowire SSLIBs.<sup>13</sup>

Inspection of the cross section image shown in Fig. 1b with additional images shown in the Supporting Information indicate that the different compositional layers of the planar SSLIB have a relatively uniform thickness and microstructure, closely resembling the intended design depicted in the schematic (Fig. 1a). The cross section image in Fig. 1g, on the other hand, reveals that the cathode and the electrolyte layers in the 3D SSLIB are highly non-uniform with respect to thickness, and that the anode layer does not conformally cover the microcolumns, as intended in the idealized structure depicted in Fig. 1c. Furthermore, the cross section image of the 3D SSLIB shows that the  $\text{LiCoO}_2$  layer has distinct columnar morphology on the microcolumn sidewalls. This type of ‘nanowire’ grain morphology is often observed when the substrate is positioned at an oblique angle with respect to the source, a regime referred to as ‘glancing angle deposition’.<sup>14</sup> Transmission electron microscopy analysis of SSLIBs prepared in the same system using a similar procedure on substrates consisting of vertically oriented VLS grown Si microwires revealed that the  $\text{LiCoO}_2$  grains have a preferred (101) crystallographic orientation along the long grain axis

(perpendicular to the metallized Si microcolumn)<sup>13</sup>. This orientation of the grain implies a highly anisotropic diffusivity for the Li ions in the cathode, with the faster diffusion occurring perpendicular to the Si microcolumn.<sup>13</sup> The LiPON solid electrolyte layer extends to the bottom of the microcolumns and coalesces at the top, leaving an unfilled region in between the microcolumns. No distinct grain structure is evident in the LiPON, consistent with it being amorphous. The coalescence of the electrolyte above the 3D microcolumns forces the Si anode layer to adopt a 2D planar geometry. In an attempt to avoid electrolyte coalescence at the top of the microcolumn array, and thus improve the battery structural uniformity, a 3D SSLIB was fabricated with a thinner LiPON layer ( $\approx 250$  nm vs.  $\approx 500$  nm). A cross section image of the resulting 3D SSLIB with the anode and current collector conformally covering the cathode layer down to the base of the array is shown in Fig. 1h.



**Figure 2.** (a) Galvanostatic charge/discharge curves collected for a planar SSLIB; C-rates 0.33 C, 1 C, 1.6 C, and 3.3 C correspond to discharge current densities  $7.1 \mu\text{A}/\text{cm}^2$ ,  $21 \mu\text{A}/\text{cm}^2$ ,  $34 \mu\text{A}/\text{cm}^2$ , and  $71 \mu\text{A}/\text{cm}^2$ . (b) Galvanostatic charge/discharge curves for the 3D SSLIB along with simulated charge and discharge curves; C-rates 0.16 C, 0.6 C, and 1.2 C correspond to  $3.7 \mu\text{A}/\text{cm}^2$ ,  $13.8 \mu\text{A}/\text{cm}^2$ , and  $27.6 \mu\text{A}/\text{cm}^2$ , respectively (c) Discharge capacity vs. cycle # for 3D SSLIB cycled at 1.2 C.

Galvanostatic charge/discharge curves for the planar and 3D SSLIB batteries at different  $C$ -rates are shown in Figs. 2a and 2b, respectively. (By definition, a 1  $C$  rate ( $\text{h}^{-1}$ ) means that the discharge current will discharge the entire battery in 1 h). The planar SSLIB capacity decreases slightly from  $\approx 21 \mu\text{Ah}/\text{cm}^2$  to  $\approx 18 \mu\text{Ah}/\text{cm}^2$  as the rates increases from  $7 \mu\text{A}/\text{cm}^2$  (0.3  $C$ ) to  $70 \mu\text{A}/\text{cm}^2$  (3  $C$ ). Given a  $\text{LiCoO}_2$  layer thickness of  $\approx 300 \text{ nm}$  in the planar battery, the initial measured discharge capacity represents  $\approx 85 \%$  of theoretical the value for  $\text{LiCoO}_2$  ( $69 \mu\text{Ah}/\text{cm}^2$  per  $1 \mu\text{m}$  thickness). Some Li is known to irreversibly alloy with Si during the first charge cycle, a loss that could be compensated for by lithiating the Si anode during deposition. The slight decrease in capacity with  $C$ -rate is consistent with the work of Dudney et al., who investigated the effect of increasing thickness of  $\text{LiCoO}_2$  on power performance of similarly fabricated thin film SSLIBs.<sup>5</sup>

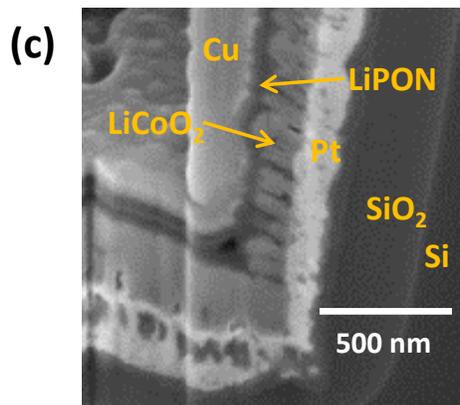
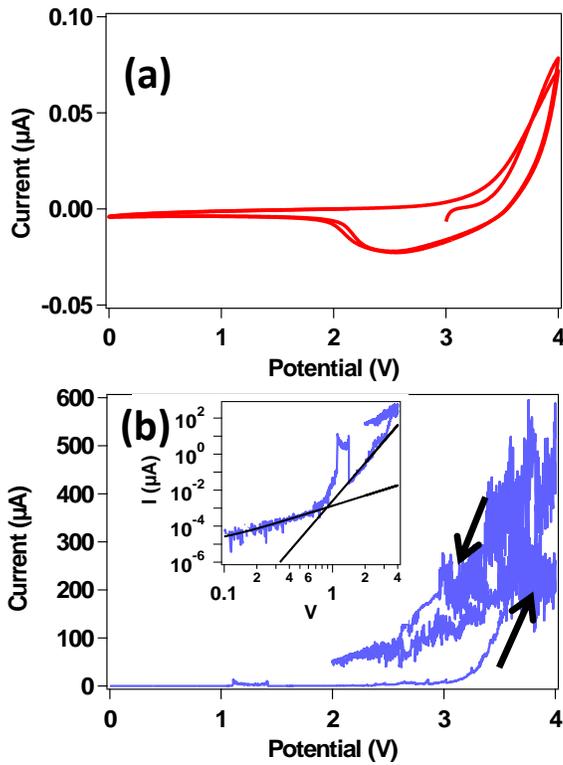
The capacity for the 3D SSLIB at 0.16  $C$  is  $\approx 25 \mu\text{Ah}/\text{cm}^2$ , slightly higher than the planar SSLIB. In principle, the two types of batteries should have equal capacities (at slow  $C$ -rate) given that both were coated with the same quantity of  $\text{LiCoO}_2$  per geometric footprint. However, in contrast to the planar geometry, the capacity of the 3D SSLIB decreases by almost 90 %, from  $\approx 23 \mu\text{Ah}/\text{cm}^2$  at 0.16  $C$  to  $\approx 3 \mu\text{Ah}/\text{cm}^2$  at 1.2  $C$ . As we demonstrate later in this paper, the dramatic decrease in the apparent capacity of the 3D SSLIB with increasing  $C$ -rate is due to the large difference in the effective electrolyte thickness for  $\text{Li}^+$  insertion/extraction near the top and bottom of the microcolumns as well as slow Li diffusion in the cathode, leading to non-uniform potential distribution and current densities and, hence, highly inhomogeneous charge/discharge rates. Discharge capacity for the 3D SSLIB measured for the first 20 charge/discharge cycles (Fig. 2c and Fig. S2) demonstrate that the 3D SSLIB can be cycled

multiple times and function as a rechargeable battery. The loss in capacity in the first 20 cycles is similar to that we earlier reported for planar SSLIBs fabricated using similar procedure (see Fig. 4 in ref. 6).

Electrochemical impedance spectroscopy (EIS) was used to estimate the ionic conductivity of the LiPON electrolyte. EIS data for LiPON electrolyte sandwiched between two block (Au) electrodes and a planar SSLIB are shown in Fig. S3. An equivalent circuit model consisting of a simplified Randles circuit in series with a constant phase element (CPE) was used to extract a LiPON conductivity of  $\approx 2.5 \times 10^{-7}$  S/cm. This conductivity is below the  $\approx 10^{-6}$  S/cm value that has been reported for LiPON and could be due to either variation in deposition process and/or brief exposure of the LiPON to the ambient just prior to anode deposition<sup>15</sup>.

In an effort to improve the structural homogeneity of the 3D SSLIBs, the average electrolyte thickness was decreased resulting in improved conformal coverage of the anode and current collector, as shown in Fig. 1h. However, the 3D SSLIBs with the thinner LiPON could not be charged and discharged due to dielectric breakdown of the electrolyte. Dielectric breakdown occurs when the electric field in electrolyte exceeds a critical value, typically  $> 10^5$  V/cm, resulting in large electronic current between the anode and cathode.<sup>16</sup> Cyclic voltammetry data (Fig. 3) show that the 3D SSLIB with the thicker electrolyte displays positive and negative currents during charge and discharge, respectively, while the battery with the thinner LiPON shows *only* positive current and with much higher magnitude (tens of nanoamps vs. hundreds of microamps). Analysis of the current-voltage data on a log-log plot (inset, Fig. 3b) for the thinner LiPON battery suggests that electron transport is by trap-assisted space-charge limited mechanism, characterized by increased slope at higher bias and considerable hysteresis, closely resembling memristors<sup>16</sup>. The likely reason for dielectric breakdown is the very thin anode-

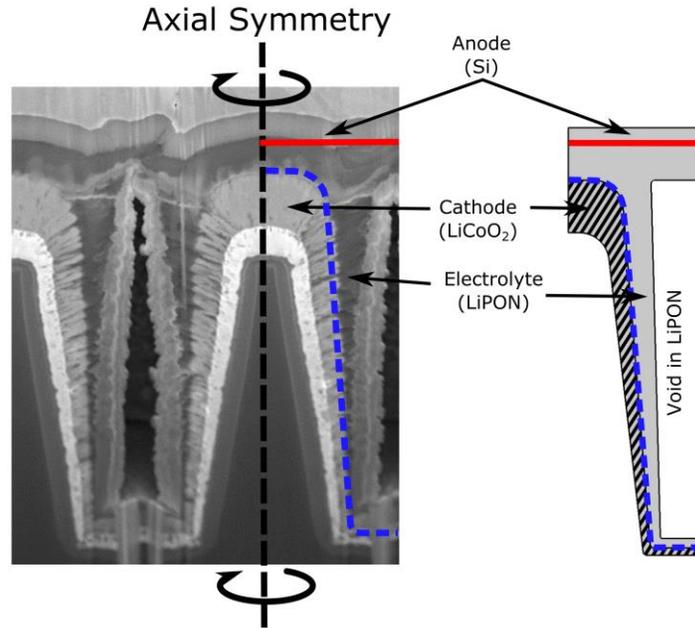
cathode separation regions (<30 nm) formed near the bottoms of the microcolumns, as shown in Fig. 3c. The combination of very thin electrolyte and high aspect ratio cathode morphology (due to the glancing angle deposition regime) lead to enhanced local electric fields that can easily exceed the dielectric breakdown strength of the electrolyte. Defect states or traps lying somewhere in the energy gap of the LiPON electrolyte could be ionized at sufficiently high fields leading to electronic current injection and breakdown.



**Figure 3.** (a) Cyclic voltammetry measured for the 3D SSLIB with nominally 500 nm thick LiPON (shown in Fig. 1g). (b) Cyclic voltammetry for the 3D SSLIB with nominally 250 nm thick LiPON (shown in Fig. 1h). (c) SEM image of the bottom corner of 3D SSLIB that exhibits dielectric breakdown.

The experimental results qualitatively suggest that lack of structural homogeneity coupled with low solid electrolyte conductivity lead to the poor 3D SSLIB performance. This explanation is further supported experimentally by EIS measurements shown in Fig. S2. The overall magnitude of the SSLIB impedance is almost equal to that of the LiPON, indicating that bulk electrolyte transport, rather than interfacial charge transport, dominates the internal battery resistance, at least at low *C*-rates. This result is consistent with a recent report of extremely low interfacial resistance measured for LiCoO<sub>2</sub>/LiPON interfaces where damage by N-atoms during sputtering was minimized.<sup>17</sup>

We developed a finite element model of the 3D SSLIB in order to gain deeper understanding of how the non-planar battery geometry, coupled with the low solid state electrolyte conductivity, affects the power capability. Details of the computation model are presented in the Supporting Information. An idealized 2D axial symmetric geometry was defined based on the conical shape elements of the 3D SSLIB cross section image, as depicted in Figure 4. Both diffusion and migration of Li ions was simulated within the LiPON electrolyte, while the transport of Li ions within the LiCoO<sub>2</sub> cathode and the Si anode was assumed to occur only by diffusion. Within the LiPON electrolyte a counter-ion, x<sup>-</sup>, with charge of -1, which does not transfer across the anode/electrolyte or cathode/electrolyte boundaries but has a mobility equal to that of Li ions was used to maintain electroneutrality.<sup>18</sup> In addition the diffusion within the LiCoO<sub>2</sub> cathode was anisotropic, with the diffusion along the surface significantly reduced compared to the diffusion normal to the surface due to the columnar nature of the LiCoO<sub>2</sub>.



**Figure 4.** 2D axial symmetric geometry used in the COMSOL model defined based on the conical shape elements of the 3D SSLIB cross section image. The anode/electrolyte boundary is shown as a red line, while the cathode/electrolyte boundary is shown as a blue dotted line.

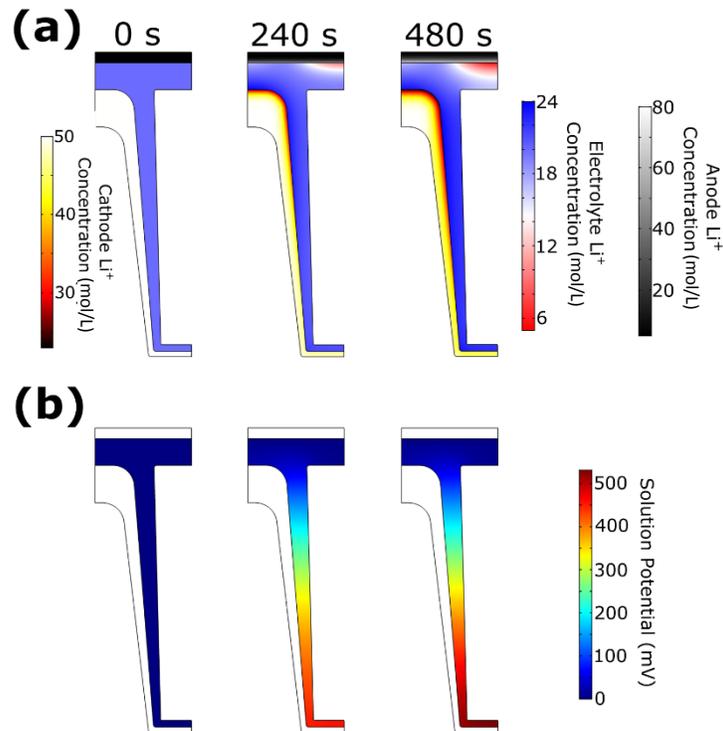
Li-ion transfer across both the anode/electrolyte and cathode/electrolyte interfaces (as shown in Fig. 4) was modeled using potential-dependent Butler-Volmer (BV) kinetic expressions. Importantly, the use of BV kinetics means that the insertion/extraction rate of Li ions at any point along the electrode/electrolyte interfaces depends on the local concentration of Li ions as well as the local activation overpotential, the latter varying dramatically during discharge/charge due to variation in the potential drop resulting from the lack of a conformal electrolyte layer.

First, we consider the simulated discharge over a range of different rates corresponding to the experimental rates. The resulting simulated cell potential vs capacity for the planar and the 3D SSLIB discharge with a LiPON conductivity of  $2.5 \times 10^{-7}$  S/cm are shown in Figs. 2 (a) and 2 (b), respectively. In the planar geometry an increase in the charge/discharge rate by a factor of  $\approx 10$  (0.3 C to 3.3 C in Fig. 2 (a)) results in an 11 % loss in capacity in the simulation as

compared to a 9% loss in capacity that is observed experimentally. Meanwhile in the 3D geometry a 7.5 fold increase the charge/discharge rate (0.16 C to 1.2 C in Fig. 2 (b)) result in an 87 % loss in capacity in the simulations, compared to a similar 90% loss of capacity observed experimentally.

We next consider the dynamics of Li-ion transport during a 1.2 C charge from an initial uniform Li-ion concentration in order to illustrate the mechanism responsible for poor battery performance of the 3D SSLIB. The concentration profiles at three snapshots during a 1.2 C rate charge are shown in Fig. 5 (a), (i) at the start of the charge cycle at  $t = 0$  s, (ii) half way through the charge at  $t = 240$  s, and (iii) at the end of the charge  $t = 480$  s. At the start of the charge cycle the Li-ion concentration is uniform, but as the charge proceeds (Fig. 5,  $t = 240$  s and  $t = 480$  s)  $\text{Li}^+$  is transported from the anode to the cathode. This transport decreases the local concentration of  $\text{Li}^+$  in the electrolyte near the anode/electrolyte (as seen in red near the anode boundary in Fig. 5 (a) at  $t = 240$  s and  $t = 480$  s) while increasing the local concentration of  $\text{Li}^+$  in the electrolyte at the cathode/electrolyte boundary (as seen as darker blue near the cathode boundary in Fig. 5 (a) at  $t = 240$  s and  $t = 480$  s). The local concentration of  $\text{Li}^+$  within the cathode near the cathode/electrolyte boundary also decreases (as seen as red near the cathode boundary in Fig. 5 (a) at  $t = 240$  s and  $t = 480$  s). However, due to the non-uniform electrolyte thickness (i.e., the non-uniform distance between the cathode and the anode) the  $\text{Li}^+$  increase in the electrolyte (and a corresponding decrease in  $\text{Li}^+$  in the cathode) occurs principally at the top of the microcolumns (at the point of the shortest distance between the anode and cathode. This preferential saturation of  $\text{Li}^+$  in the electrolyte (and depletion of  $\text{Li}^+$  in the cathode) near the cathode/electrolyte interface at the top of the microcolumns has the subsequent effect of reducing the local flux of  $\text{Li}^+$  across the cathode/electrolyte boundary at the top of the microcolumn. As the charge proceeds the

transport of  $\text{Li}^+$  across the cathode/electrolyte interface is forced further down the microcolumns, introducing a larger potential drop across the electrolyte due to its finite conductance, as shown with the progression of solution potential in Fig. 5 (b). The depletion/saturation of the cathode interface in the non-uniform geometry, coupled with the finite electrolyte, reduces the performance of the battery. In addition, the slow diffusion of  $\text{Li}^+$  within the cathode reduces the capacity and results in underutilizing the cathode material. Taken together, these simulations show that cell performance is limited by the non-uniform distance between the anode and cathode in combination with the limited  $\text{Li}^+$  transport in both the electrolyte and the cathode. Simulations would suggest that cell performance can be improved by increasing the conductivity of the LiPON electrolyte, increasing the diffusion of  $\text{Li}^+$  in the cathode or by changing the geometry of the 3D SSLIB to have a constant distance between the anode and cathode (constant thickness electrolyte).



**Figure 5:** Concentration (a) and potential (b) profiles for three time points (0 s, 240 s, and 480 s) during a 1.2 C-rate charge from an initially uniform  $\text{Li}^+$  concentration for the 3D SSLIB.

In summary, we have demonstrated rechargeable 3D solid state Li-ion batteries with microscale internal dimensions, fabricated using materials and thin film deposition methods compatible with semiconductor device processing. We have shown that the power performance of these 3D SSLIBs lags significantly behind that of similarly prepared planar batteries, and that the origin of this poor power performance is the combination of structural inhomogeneity of the 3D SSLIB with low electrolyte ionic conductivity. Together, the inhomogeneity and low electrolyte conductivity lead to a highly non-uniform internal current density distribution and poor cathode utilization. However, increasing the electrolyte conductivity to  $10^{-5}$  S/cm would allow a 3D SSLIB to maintain (with a less than 1% loss in capacity) the superior performance compared to planar batteries, even with an inhomogeneity ratio (the ratio of the longest to shortest path from the anode to the cathode) of 0.2.

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