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| | Experiment title: <i>In situ</i> structural study of silicon anodes in lithium-ion batteries | Experiment number: MA-3459 |
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| Names and affiliations of applicants (* indicates experimentalists): Samson Yuxiu Lai* (Physics Dept., Institutt For Energiteknikk, Kjeller, Norway) Kenneth D. Knudsen* (Physics Dept., Institutt For Energiteknikk, Kjeller, Norway) Trygve T. Mongstad* (Solar Energy Dept., Institutt For Energiteknikk, Kjeller, Norway) Jan Petter Mæhlen (Energy Systems Dept. , Institutt For Energiteknikk, Kjeller, Norway) Asbjørn Ulvestad* (Energy Systems Dept. , Institutt For Energiteknikk, Kjeller, Norway) Volodymyr Yartys* (Energy Systems Dept. , Institutt For Energiteknikk, Kjeller, Norway) | | |

Report:

This report describes experiment MA-3459, which was aimed at studying the evolution of the local structure of silicon during *in situ* lithiation as a lithium-ion battery cell anode. We performed two types of *in situ* experimental configurations, although we experienced several challenges. The data analysis is forthcoming due to its complexity, which will become apparent in the detailed descriptions below.

Beamline configuration, alignment

The first shift was spent on beamline configuration, solving issues with monochromators, and alignment using LaB₆. We chose an energy of 50 keV to obtain a high *q* for pair distribution function analysis, since most of the Si of interest was amorphous or would become amorphous upon lithiation.

Ex situ - capillaries

We first tested and measured several types of Si sources and other battery materials such as the pouch cell, Li foil, Cu current collector, etc. as reference materials so that we could take into account their contribution later in the data analysis. Capillaries were prepared in advance and mounted onto a goniometer head using beeswax as depicted in Figure 1. However, several hours were lost in the second shift because the position of the tungsten carbide anti-scatter plate was misaligned. The misalignment only became apparent upon analysis of the first datasets followed by additional reference measurements on an empty capillary that yielded

strong crystalline peaks. As a result, the plate had to be re-aligned and several samples had to be re-measured.

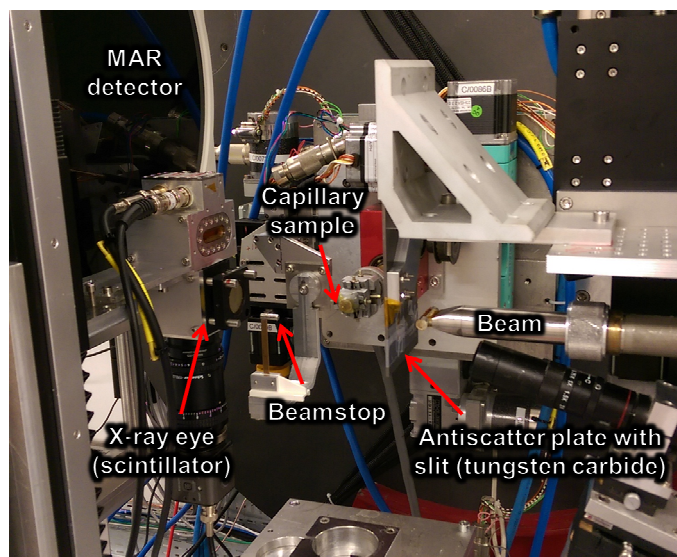


Figure 1. Diagram of the capillary mounted on goniometer head in *ex situ* measurements.



Figure 2. (top left) Planar pouch cell. (top right, bottom right) X-ray eye is able to observe the edge of the electrode. (bottom left) Pouch cell mounted in beam path and connected to portable potentiostat

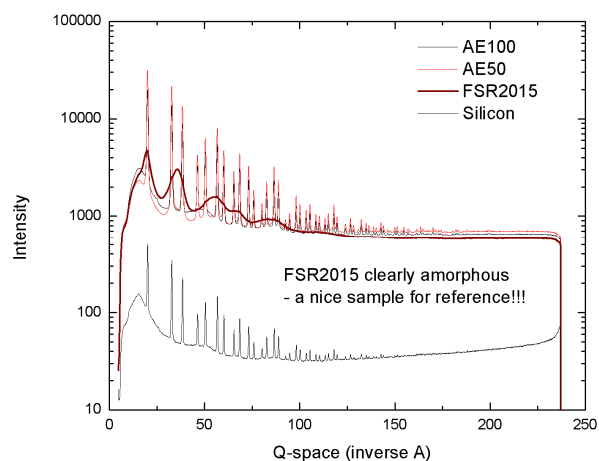


Figure 3. Reference data from *ex situ* capillary measurements.

***In situ* experiment #1 – through-thickness pouch cell**

Our first *in situ* measurement used a simpler approach with measuring coin-cell sized electrodes in a pouch cell. The cell setup and results of the x-ray eye are shown in Figure 2. Because we had fabricated many of these cells before and it is planar in design, the cell cycled moderately while it was measured. However, because of the through-thickness scattering, the Si signal of interest is convoluted by the Cu current collector, Li metal, and polymer separator. Data analysis is in progress and is aimed at deconvoluting the signals.

***In situ* experiment #2 – pouch bar cell**

In our second experiment, we attempted a novel, more radical approach by measuring the electrode in the edgewise direction instead of through-thickness. This approach was challenging due to the thickness of the Si electrode being about 10 to 15 microns. However, with the aid of the x-ray eye, we were able to visualize each layer of the cell when viewed edgewise, as shown in Figure 4. After reducing the slits, although the counts were lower, we could measure the scattering from FSR roughly each layer of interest.

However, in our cells, Al had been used as a current collector for the Li metal counter electrode instead of Cu. This was not ideal, and although cells still operated as observed in *in situ* experiment #1, the mechanical stress of flexing the pouch bar cell and/or the pooling of the electrolyte solution away from the electrode disabled the battery cell from cycling. Although

we could observe different layers of the cell edgewise, we were not able to make *in situ* measurements of the cell as it cycled.

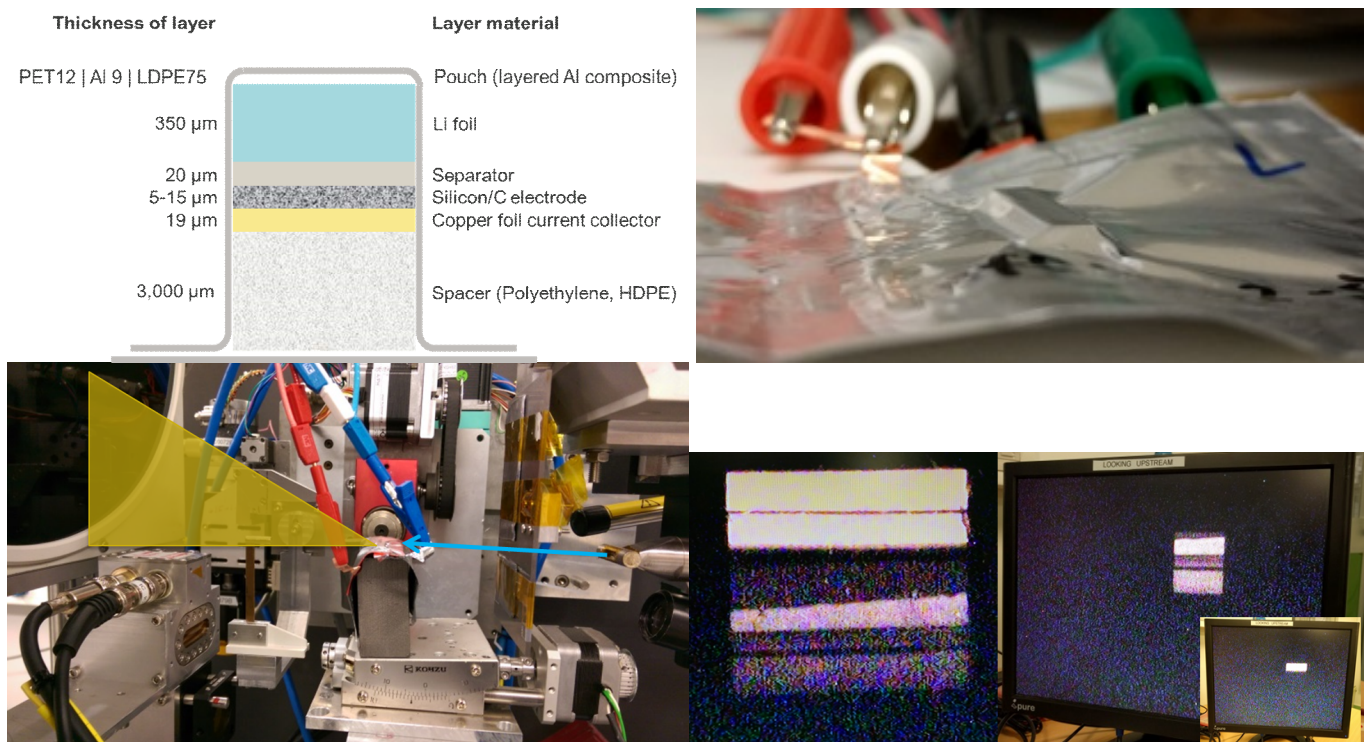


Figure 4. (top right) Sealed, prepared pouch bar cell as viewed at a glancing angle. (top left) Cross-sectional diagram of the pouch bar cell. (bottom left) Pouch bar cell as mounted on a metal block on a Huber stage with arrows and triangle depicting incident x-ray beam and scatter beam paths, respectively. (bottom middle, right) Real-time X-ray eye video feed of the bar cell layers. (bottom right, inset) X-ray eye view after slits are reduced the beam to a layer of interest.

***In situ* experiment #3 – pouch bar cell, silicon nitride**

Our third *in situ* experiment was a repeat of experiment #2 but with silicon nitride. Silicon nitride also has good performance as a Li-ion battery anode with some interesting phenomena that occur in the first lithiation cycle. We aimed to use the evolution of the local structure of Si to help explain its performance, but encountered the same issues as in experiment #2 because of the common design. Anyhow, some electrochemical activity was recorded since the silicon nitride operates differently chemically from pristine Si but it was less than ideal.

Conclusions

We were partly successful in conducting different types of *in situ* x-ray scattering experiments for Li-ion battery cells based on Si anodes. The degree of success also depends on how easily we can deconvolute the scattering signal and eliminate or reduce the contributions from foreign parts of the pouch cell. The pouch bar cell design demonstrated its feasibility in large part thanks to the x-ray eye equipment, which was surprising given that beam alignment to the layer of interest was considered the most challenging part of the experiment.

Improvements for future experiments

There are several points of improvement, both scientific and logistical.

- 1) Shipping of batteries was a significantly larger challenge than expected. Although we researched the requirements and regulations, ultimately our approach faltered because

we were misinformed about the expected delivery time of the batteries (on the order of weeks instead of days) by cargo plane.

- 2) Although our through-thickness pouch cells were previously tested many times, our pouch bar cell was less robust and did not perform as expected. However, we are certain the solution is to replace the Al current collector with Cu, which is also thicker and stronger. These improvements can take place immediately.
- 3) At the same time of this improvement in cell design, we are augmenting the pouch cell to incorporate Kapton windows for increased x-ray transparency, reduction of noise, and minimizing the signal contribution to the pouch cell material. We will push the boundary of this design principle as far as possible, including modifying the internal electrode cell separator with a Kapton window.
- 4) Further, sample alignment and motor control consumed a significant amount of time. Besides improving the pouch cell, we plan to devise our own sample holder that would provide more reliable control with less influence on the cell's performance.