Microstructuring of Lithium-Ion Battery Electrodes with Picosecond Lasers

Lithium-ion batteries are the cornerstone for modern power storage technologies such as consumer electronics or electric vehicles. Novel picosecond lasers enable structuring of battery electrodes with very high precision and low heat impact. The resulting diffusion channels created by this technology lead to significantly enhanced performance and extended lifetimes of Lithium-ion batteries.

Background

Lithium-ion batteries (LIBs) are currently the dominant solution for most applications of electrochemical energy storage. The transition from internal combustion engines to electric mobility is especially prevalent in the automotive sector and is largely based on this novel technology. In line with this demand, significant global production capabilities are forecast to be built up in the coming years and decades [1].

A central drawback of the technology, however, is the limited fast-charging and discharging capability of current LIBs. This issue results from the diffusion limitations caused by the porous structures of typical battery electrodes as depicted in Fig. 1.

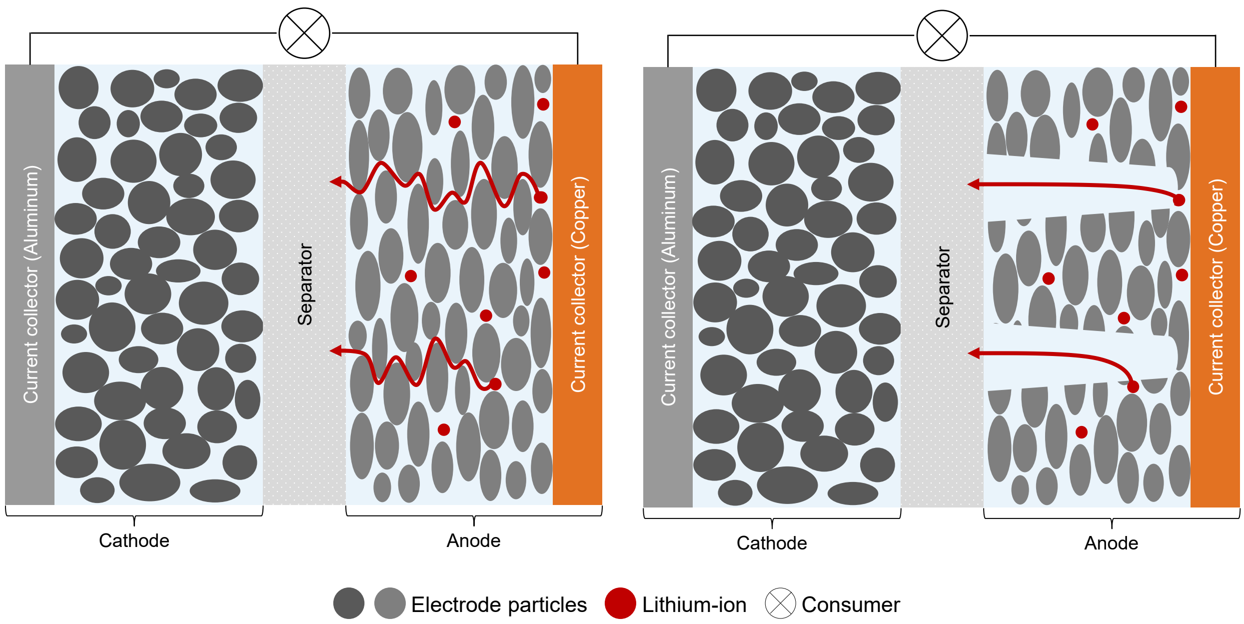

Figure 1: Schematic representation of a Lithium-ion battery. Left: Illustration of tortuous ion diffusion paths in a conventional graphite anode. Right: Shortening of diffusion paths through electrode structuring.

Electrodes of a conventional LIB typically consist of a multi-material compound, allowing the 'intercalation' process to occur, i.e. the reversible insertion of ions. In order to prevent a short-circuit, the anode and the cathode are separated by an electrically insulating separator in the LIB. When the cell is charged or discharged, Lithium-ions diffuse from one electrode to the other in a liquid electrolyte. The porous structure of the battery electrodes results in long and winding ion diffusion paths during this process (Fig.1 left), which lead to large ionic resistances of the cell. The introduction of microscopic channels in the electrodes offers a solution to this limitation by shortening the ion diffusion paths (Fig.1 right) and reducing electrochemical overpotentials. Especially thick and highly compacted graphite anodes, which are key to an increase of the energy density of future LIBs, benefit from the approach. LIBs containing structured graphite anodes show a significant performance increase in comparison to their unstructured counterparts [2]. Furthermore, LIBs with structured electrodes exhibit an enhanced lifetime through the reduction of degradation effects such as Lithium plating [3]. In addition, it can be shown that the electrolyte filling process, which largely contributes to the production costs of LIBs, can be significantly accelerated through electrode structuring [4].

Laser Material Processing

Pulsed laser radiation has proven to be a versatile tool for the introduction of diffusion channels into the electrodes with micrometer precision. Novel ultrashort-pulsed laser sources allow the selective ablation of electrode coatings with low heat input into the surrounding material. Figure 2 shows a scanning electron microscopy (SEM) image of a laser-structured graphite anode. On the upper right part of the figure, ablation cones are clearly visible, stretching down nearly to the current collector foil (Fig. 1 right). The holes show minor deviations in their upper diameter, which are due to substrate inhomogeneities such as particle agglomerations. The laser holes are arranged in a hexagonal pattern with a pitch distance of 100 µm, which is optimized to the electrochemical properties of the electrode.

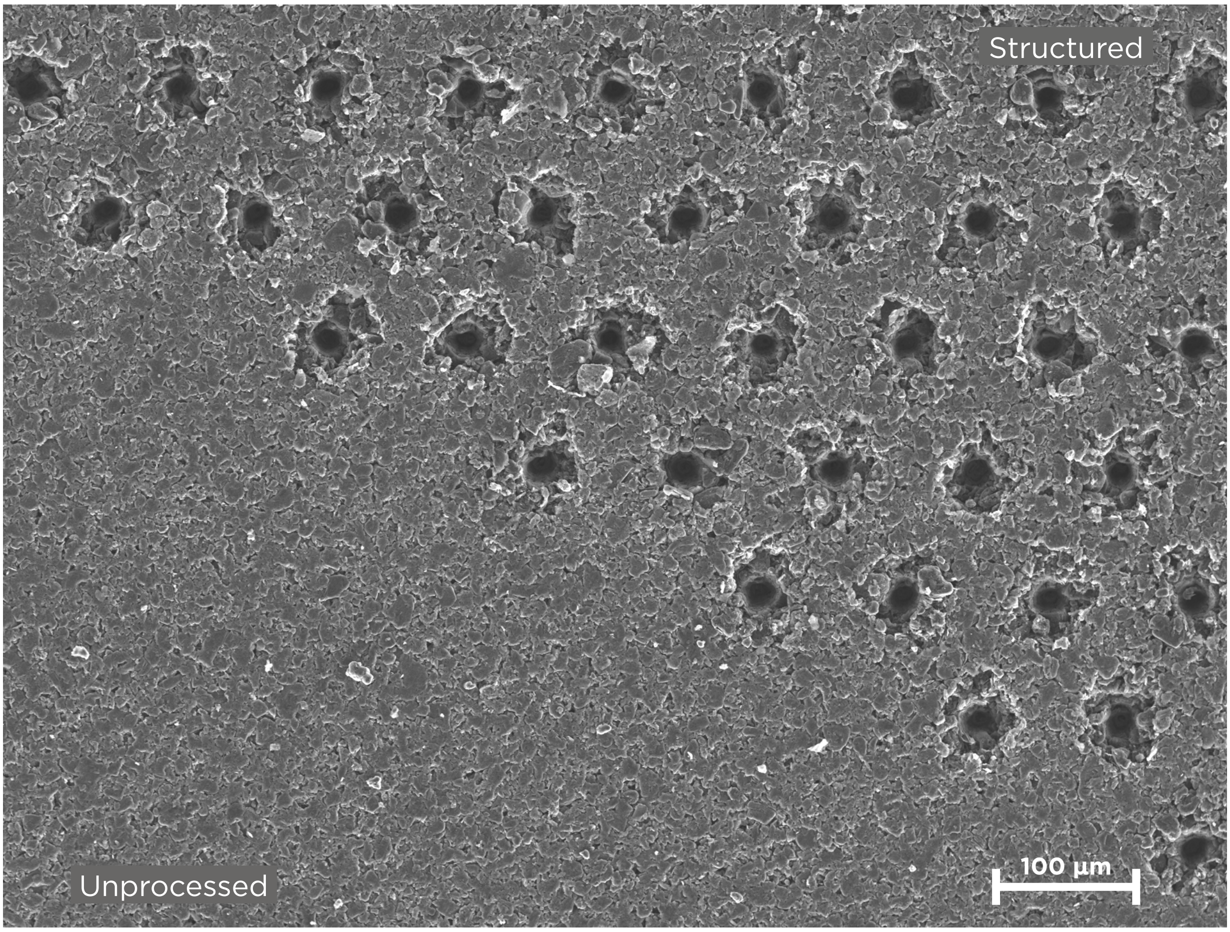

Figure 2: SEM image of a graphite anode in an unprocessed (lower left) and structured condition (upper right).

The holes were created with a picosecond laser, emitting laser pulses at 1064 nm with a typical length of 8 ps at a medium power of up to 45 W (Dart, Novanta Inc.). Figure 3 shows the laser source in a laboratory setup for the micromachining of battery components. The beam is widened from 3 mm to 12 mm diameter with a beam expander, subsequently deflected using a scan head with a clear aperture of 21 mm with galvanometer-driven mirrors (Racoon, Novanta Inc.) and finally focused with an F-Theta lens (focal length 160 mm) onto the substrate. Whilst the holes shown in Figure 2 were obtained at a pulse repetition rate (PRR) of 5 MHz and corresponding pulse energies of approx. 5 µJ, the laser source can cover PRRs of up to 15 MHz with pulse energies of up to 300 µJ (at 100 kHz PRR). These properties enable precision control of the required geometric structures in order to achieve full optimization of the electrochemical characteristics of the electrode. The ability to drill holes with high aspect ratios i.e. small diameters at large depths, is also highly desirable for a low material ablation and a high capacity LIB.

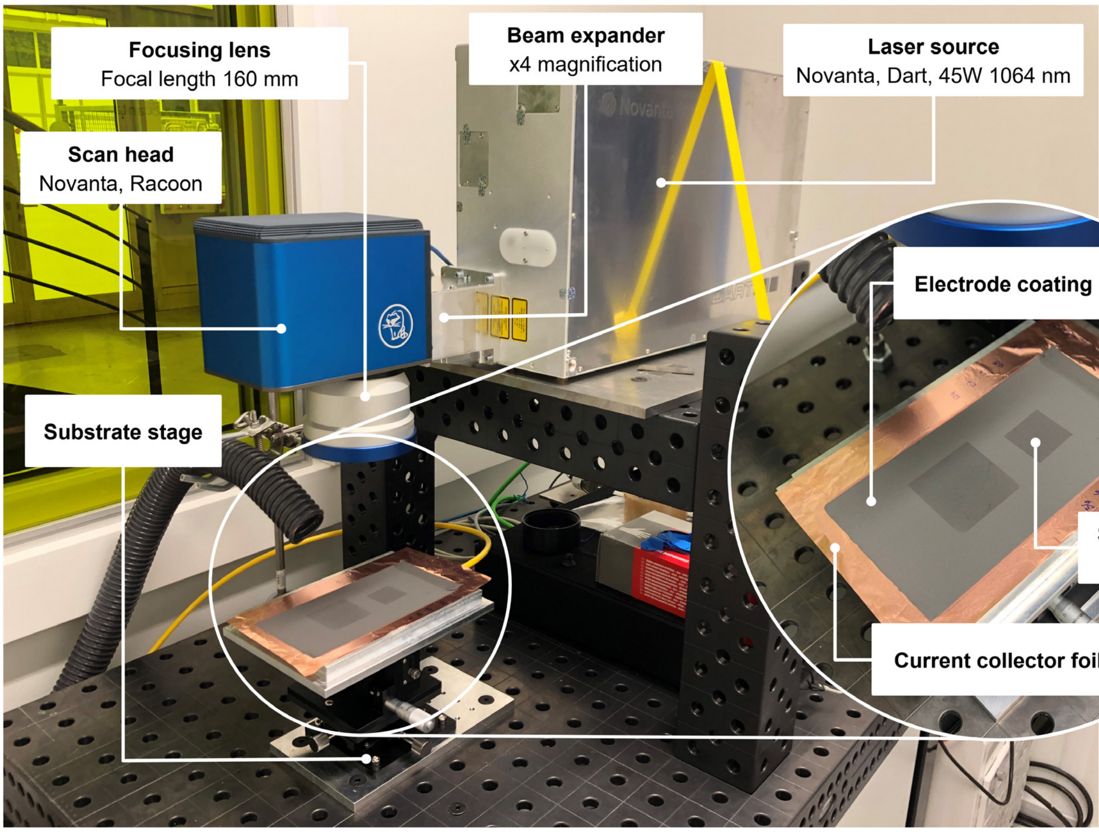

Figure 3: Laboratory environment for laser processing of battery electrodes.

Outlook

The transfer of laser structuring from the laboratory scale to an industrial scale will primarily require a significant reduction in the process time. This may be achieved by combining ultra-short pulsed laser sources with novel solutions for beam deflection such as polygon-based scan heads (POLYtek^{TM}, Novanta Inc.) and parallelization approaches [5]. Furthermore, a concept for the integration of laser structuring into the manufacturing chain of battery electrodes is needed. Modern pulsed laser sources such as the Novanta Dart laser, which combines a low footprint with a high operational stability, permit maximum flexibility for this task. Modern laser beam sources show constantly improving beam qualities, increasing average powers and falling costs, which will pave the way for the future industrialization of electrode structuring.

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