https://doi.org/10.1038/s41565-023-01529-6

Nanotechnology for electrochemical energy storage

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Adopting a nanoscale approach to developing materials and designing experiments benefits research on batteries, supercapacitors and hybrid devices at all technology readiness levels.

Initially conceptualized as an approach to achieve materials control one atom at a time, nanotechnology has expanded its scope through the decades. Norio Taniguchi, who coined the term 'nanotechnology', envisioned it as "the processing of separation, consolidation, and deformation of materials by one atom or one molecule"[1]; this interpretation led to notable advances in the field of microscopy. However, the discovery of nanoscale objects whose properties are size-dependent (for example, quantum dots or carbon nanotubes) overcame this definition. An *ACS Nano* editorial in 2015 nicely discusses this paradigm shift[2].

Nowadays, nanotechnology can be considered a way of doing research in which nanoscale understanding informs the design and engineering of disruptive materials properties and/or device performances. Perhaps nowhere else more than in the field of electrochemical energy storage, this research approach has been so meaningful, as this area of research is particularly susceptible to materials investigations at the nanoscale. Indeed, nanotechnology has produced tangible outcomes capable of addressing issues and problems at one or more technology readiness levels (TRLs)[3,4].

A straightforward example is $LiFePO_4$ (LFP). Micro-size LFP was initially synthesized and proposed as a positive electrode active material for non-aqueous Li-ion storage by John B. Goodenough and his collaborators in 1997[5]. However, because of the poor LFP electronic conduction properties, the initial electrode formulation used a 25% electronically conductive carbon additive. Between 2000 and 2010, researchers focused on improving LFP electrochemical energy storage performance by introducing nanometric carbon coating[6] and reducing particle size[7] to fully exploit the LFP Li-ion storage properties at high current rates. These nanotechnology-led advancements, ranging from TRL 1 to 4, paved the way for the development of large-format LFP-based Li-ion cells for higher TRLs, a solution also adopted by BYD, an electric vehicle company, to improve packing efficiency and eliminate the use of small modules[3].

Another industrially relevant, nanotechnology-enabled advancement is the development of TiC-derived nanoporous carbon materials[8] in the second half of the 2000s. These carbons, capable of efficient non-Faradaic charge storage processes, were employed by Skeleton Technologies, a commercial supercapacitor manufacturer[9] operating at TRLs ≥ 5, to produce high-power cells with a 72% energy density increase compared with the then commercial supercapacitor devices.

Other historically relevant examples of nanotechnology applications that helped develop and launch Li-ion batteries into the market as commercial products are based on the fundamental investigation of non-aqueous liquid electrolyte solution components (for example, use of ethylene carbonate as solvent or adoption of fluorinated inorganic salts) and their influence on the formations of interphases (for example, solid electrolyte interphase) at the electrode|electrolyte interface in the cell[10].

The fundamental understanding of interfaces and interphases is particularly important as low TRL research work carried out via in situ or operando measurements unveil mechanistic insights[11] that can inform the design of better performing cell components. However, the transfer of knowledge from these measurements and analyses is possible only if a tailored experimental design, representative of the practical cell's conditions, is considered. This approach is particularly valuable in identifying the cause of a particular cell failure mechanism and finding possible solutions to circumvent, or overcome, the issue.

These examples demonstrate the importance of understanding nanoscale materials' properties at any TRL, especially when intense materials manipulation occurs to produce devices. This latter aspect is particularly relevant in electrochemical energy storage, as materials undergo electrode formulation, calendering, electrolyte filling, cell assembly and formation processes.

We are confident that — and excited to see how — nanotechnology-enabled approaches will continue to stimulate research activities for improving electrochemical energy storage devices. *Nature Nanotechnology* will always be home for advances that have the 'nano' aspect as the core of the research study, at any TRL.

Published online: 13 October 2023

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