Research Diary

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Design and Development of Functional Materials for Energy Storage Devices @ CARBON Lab, IIT Hyderabad

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“Energy” is in the core of every economic, environmental, and developmental aspect impacting the global economy significantly. At present, the primary energy sources in the world are oil, coal, and natural gas. Considerable use of these energy sources has led to colossal CO2 emissions that are acidifying our oceans and also responsible for global warming. This has raised a question worth pondering that if any energy source can enable modern civilization to secure a clean, efficient, and reliable, and sustainable energy supply for all people and reduce the imprint on air pollution of the internal combustion engine and coal-fired power plants.

To address these issues, we are presently exploring renewable and rather clean energy sources like solar, wind, geothermal, ocean, and other carbon-neutral sources. However, due to the intermittent nature of these energy sources, we need state-of-the-art and more efficient energy storage technology to make effective utilization of energy as per the demand. Rechargeable batteries and supercapacitors have thus received tremendous attention in the last two decades or so. Among them, Lithium-ion batteries (LIBs) are one of the widely explored electrochemical devices used in smartphones, laptops, and most other consumer electronics. Commercially available LIBs have graphite electrodes with a theoretical capacity of 372 mAh/g, which limit the use of LIBs in the electric car, grid, and even for space application. Here in our lab, we aim to design and develop more efficient electrode materials for advanced lithium-ion batteries and other battery chemistry such as lithium-sulfur (Li-S), lithium-carbon dioxide (Li-CO2) and, supercapacitor which can be used in electric vehicles to aircraft space applications as summarized below:

Advancement in lithium-ion batteries for accelerating the devices:

We first time demonstrated the use of the candle soot-based carbon nanomaterial for high-rate lithium-ion batteries to address the long-time charging issues associated with the adoption of electric vehicles across the world. Further, the catalytic graphitization of resorcinol–formaldehyde xerogel enables a fine balance in graphitic content in hard carbon addressing the challenges of capacity fading and poor electronic conductivity associated with hard carbons as an anode in Li-ion batteries (LIBs). Besides modifying the physicochemical properties of these carbon materials, we also focused on the novel design aspects of anodes to achieve high rate performance. Unlike the conventional planar electrodes (2D) with higher mass loadings, we even extended the concept of 3D electrodes to fabricate hierarchical and hybrid 3D electrodes using a combination of Carbon MEMS approaches with electrospinning, hydrothermal synthesis, or drop-casting. Simple strategies like the use of pencil trace coating on the current cum collector suppressed the side reactions and facilitated in achieving excellent capacity retention. Furthermore, a combination of MOF with 3D carbon electrodes was helpful in achieving significantly higher reversible capacities in these electrodes.

Lithium-sulfur (Li-S) batteries for long-range electric vehicle application:

Lithium-sulfur (Li-S) batteries present a promising solution to replace the conventional lithium-ion batteries (limited driving range ~160 km) due to the high theoretical specific capacity (1675 mAh /g; driving range ~500 km) and specific energy density (2500 Wh /kg) of the sulfur cathode.

However, the commercialization of the Li-S battery is challenging because it suffers from the electrochemical intermediates (polysulfides) dissolution in an organic electrolyte which lowers the columbic efficiency and cycle life of the Li-S battery. These issues of Li-S battery are being addressed at CARBON Lab by developing carbon-metal oxide material as a host and interlayer for Li-S battery. It has been observed that the conducting carbon-based sulfur host and interlayer can confine polysulfides physically and also chemically to overall improve the cycle life of the battery. The use of these strategies also shows effective utilization of the active electrode of Li-S cell for long-range application of the devices with low environmental impact.

Supercapacitor for boosting power of electric vehicle:

The supercapacitor is another energy storage device that can be recharged instantly and can provide the necessary large amount of power to accelerate the vehicle, but they have limited energy density compared to the battery system. Here, we present an ingenious approach to convert bio/other waste (Borassus Flabellifer fruit skin and cork powder waste) into carbon and also directly used candle soot carbon to fabricate electrodes for the development of sustainable supercapacitor as an energy storage device with optimum energy and power density.

In yet another approach, we developed metal sulfide/oxide-candle soot-derived carbon composites for high-performance supercapacitor applications. As-developed symmetric as well as asymmetric devices show significantly improved electrochemical performance compared to the existing commercial carbon-based supercapacitors and therefore, have a high potential for electrical vehicle applications.

Rechargeable Li-CO2 battery chemistry for Mars exploration:

Space agencies worldwide are exploring the red planet (Mars) in the search of signs of life. However, Mars exploration missions require a robust, highly efficient, high-energy-density with long cyclic stability rechargeable batteries that can function in even harsh conditions. Here, we have introduced the first time a functioning prototype of Li-CO2Mars battery chemistry using a porous carbon cathode made from candle-soot carbon. The development of high energy density Li-CO2-Mars batteries can also be justified in terms of significant mass and volume reductions, both of which are essential in the Mars Lander and Rover missions. Another aspect of this work is to develop efficient Li-CO2 battery systems and provide a striking option to fix CO2 emissions and environmental protection.

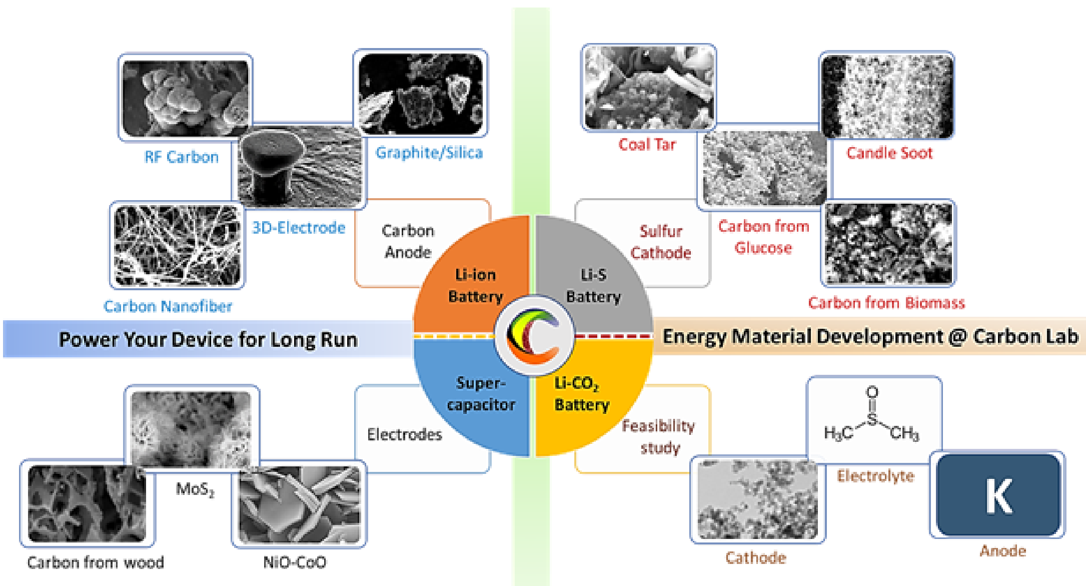

Fig. 4: Schematic of design and development of functional materials for energy storage devices @ CARBON Lab