

The materials making potassium-ion batteries possible

You are probably familiar with lithium-ion batteries that can be found everywhere from inside our mobile phones to electric cars. However, lithium's larger brother potassium may soon find its way into the batteries that power our everyday lives. Dr Titus Masese at the National Institute of Advanced Industrial Science and Technology in Osaka, Japan, has been developing new materials for electrodes to help overcome some of the current limitations of potassium-ion battery technologies to allow them to reach their potential as a promising low-cost rechargeable battery material for energy storage.

An electrical battery is any device that stores energy that can be converted to electrical energy. A basic battery provides electricity, or a flow of electrons, by having a positively charged cathode and negatively charged anode at each end, with an electrolyte, a conductive solution, in between.

When a battery is connected to an electrical circuit, chemical reactions within the battery cause electrons to start building up at the anode. Eventually, this pile-up of electrons becomes unstable and will move through the electrolyte separating the anode and cathode, and flow around the circuit, providing the necessary electrical power.

However, each of these chemical reactions depletes the stored potential energy in the battery. Rechargeable batteries try to overcome this by reversing the oxidation and reduction reactions, the chemical reactions that occur at the cathode and anode and, this time, convert electrical energy to chemical energy.

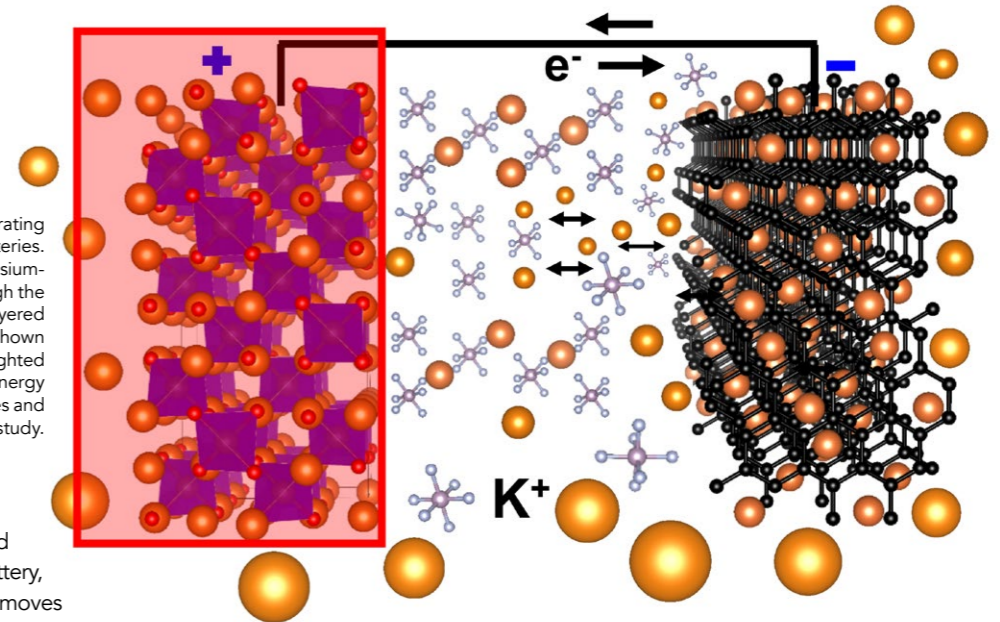
One of the most famous types of rechargeable batteries is the lithium-ion battery, where its high-power density makes it ideal for portable, energy-hungry devices like smartphones. However, lithium-ion batteries are not the only option for rechargeable battery technologies.

Dr Titus Masese at the National Institute of Advanced Industrial Science and Technology in Osaka, Japan has been working on new, potassium-based materials for developing potassium-ion based rechargeable batteries. There are good motivations for doing this. Developments in higher-energy, longer-lifetime and lower-cost battery technologies are a key part of the necessary energy storage strategy required for a more sustainable future, and potassium-ion batteries may offer a lower-cost alternative, partly as potassium is over eight hundred times more abundant on Earth than lithium.

A MATERIALS CHALLENGE

Part of the reason that phones today don't come with potassium-ion batteries is some of the technical challenges with their development that people like Dr Masese and his colleagues are working to overcome. The name of lithium or potassium-ion batteries comes from the type of chemical element

Schematic illustration of the operating mechanism of potassium-ion batteries. Akin to lithium ion batteries, potassium-ions shuttle back and forth through the electrolytes to the electrodes. A layered cathode and graphite as anode is shown for brevity. The cathode (highlighted in red) principally restricts the energy density of potassium-ion batteries and was the central focus of this study.



that is embedded in the electrodes. This ion, which is oppositely charged to the electrons produced in the battery, is released from the electrodes and moves in the opposite direction to the electron. The movement of the ions is as crucial for the battery performance as the movement of the electrons: if the ion fails to move, the battery can discharge and fail to provide energy.

What Dr Masese and his colleagues have been successfully able to do is create honeycomb layered cathode frameworks that incorporate potassium ions and are capable of sustaining very high voltages. One of the challenges for using potassium ions in rechargeable batteries is that their large sizes can make it difficult to incorporate them in the tight-packed lattice frameworks that make up the type of electrons used in lithium-ion batteries. In an ideal battery, the ions would be fast to release from the framework, move through the electrolyte and then be reincorporated back into the frameworks as required.

The honeycomb structures that Dr Masese and his colleagues have pioneered currently show the largest voltage for any layered cathode material, meaning it could potentially show the highest energy delivery as part of a battery. He has also been working to incorporate these into rechargeable potassium-ion batteries as a step towards more practical potassium-ion battery technologies.

DURABLE ELECTRODES

The secret of the success of Dr Masese's honeycomb structures lies in their ability to facilitate reliable potassium ion recombination, a significant challenge

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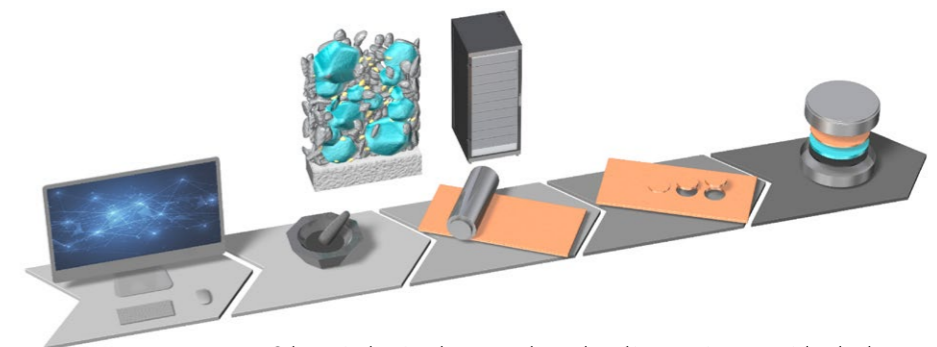
due to the large size of the potassium ions. Many electrode materials are made from highly organised, regular crystalline structures, so any gaps left by a departing ion will remain in the same place. However, recombination processes and unwanted chemical reactions between the electrolyte and electrode can lead to damaging and aging of the battery. This is why many phones undergo significant deterioration of battery performance even within a few years of manufacture.

These honeycomb materials have shown to be thermally stable and maintain the high voltages they are capable of producing, which bodes well for the

potential lifetimes of potassium-ion batteries based on these cathodes. It is not just the cathode though that is important for battery stability and durability. As the electrolyte can also play a role in detrimental chemical reactions, this too must be as benign as possible.

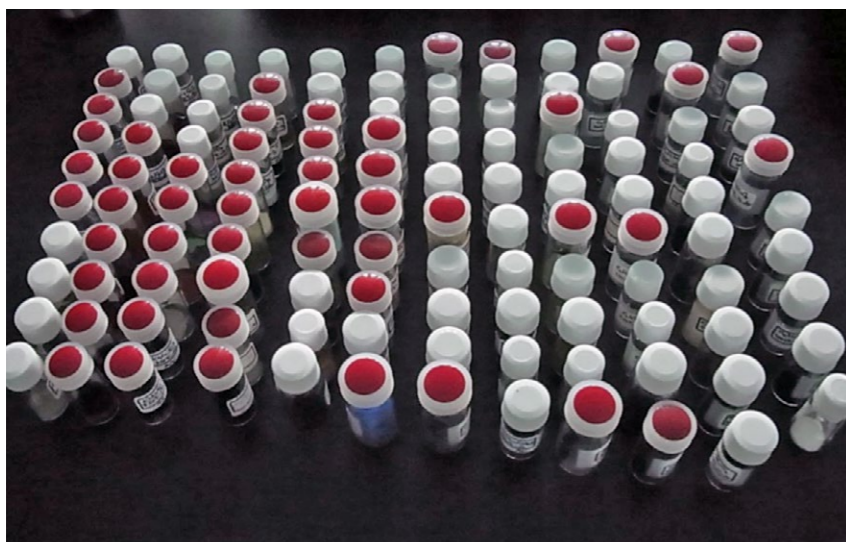
FUTURE OF ELECTROLYTES

Dr Masese and his colleagues have been using ionic liquids as the electrolyte materials in the development of potassium-ion cells, or tellurate-based materials where a solid electrolyte is desirable. Ionic liquids are unusual in their behaviour as they are liquids that contain dissolved salts that



Schematic showing the protocols employed in screening potential cathode materials for rechargeable potassium-ion batteries. Potassium-based compounds were screened using reliable computational processes after which potential candidates were selected. The selected material powders were assembled as electrode materials and their performance evaluated in coin cells using standard electrochemical measurement procedures.

There are multiple possible applications for potassium ion batteries. These range from industry, renewable energy, domestic uses, electric vehicles and mobile phones.



Snapshot of the various novel potassium-based compounds (cathode candidates) synthesised over the course of this study.

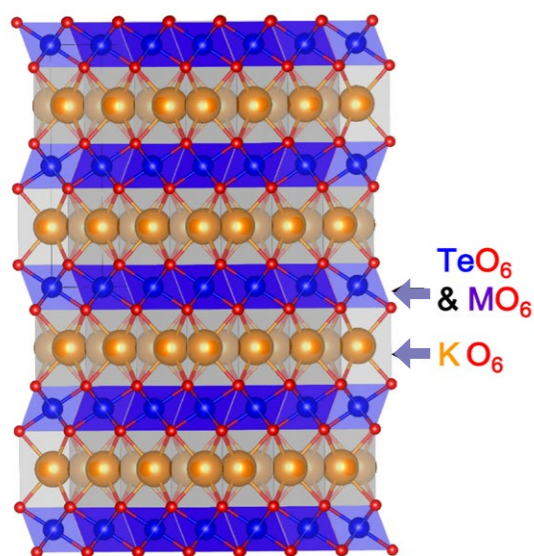
Dr Masese's materials are helping to herald in the post-lithium-ion battery age.

exist as charged ions. Conventional electrolytes contain organic solvents, rendering them flammable. They also tend to decompose at high voltages and temperatures. Ionic liquids do not contain flammable organic solvents. Therefore, they are safe and stable at high voltages and high temperatures which are beyond the capacity of conventional electrolytes.

Solid electrolytes are also highly desirable to combat some of the safety concerns about rechargeable ion batteries. Liquid electrolytes can leak if the battery is damaged and are also highly flammable, which is the origin of many of the high-profile stories about mobile phone battery fires. The problem with solid electrolytes is that, although they are better from a safety perspective, they

CRYSTAL STRUCTURE

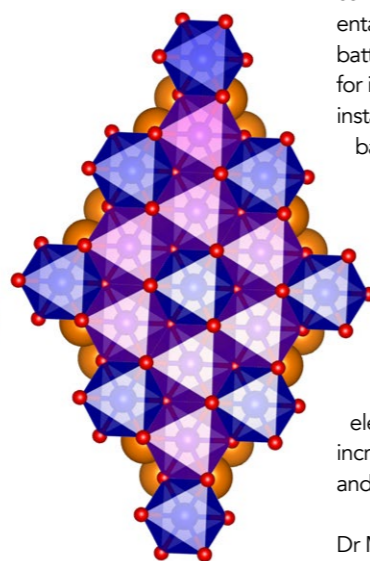
P2-Type layered structure



SIDE VIEW

The figure on the left shows the layered crystal structure. On the right is the same structure viewed from above.

Honeycomb structure



TOP VIEW



Dr Masese at work in the lab.

do not show the same efficiency as their liquid counterparts, but Dr Masese has demonstrated that the tellurate-based materials do show high conductivity for the potassium ions and may well play an important role in the development of solid electrolytes for potassium-ion batteries of the future.

LIGHTENING THE LOAD

One of the key advantages of the potassium-ion batteries that Dr Masese is helping to realise is their very high voltage capabilities, that he has demonstrated through the performance of the electrode material. High-voltage supplies reduce the need for so many cells within a battery pack. This then entails small volume, cost and weight battery packs, something that is essential for improving the performance of, for instance, electric vehicles. The 85 kWh battery pack in the Tesla Model S weighs in excess of an enormous 500 kg and accounts for nearly a quarter of the total weight of the car. Although 40 litres of petrol weighs around 30 kg and there is the weight of the fuel tank and fuelling system to consider, finding a solution for the heavy weight and bulky sizes of electrical batteries would dramatically increase the feasibility of electric vehicles and significantly increase their efficiency.

Dr Masese's materials are helping to herald in the post-lithium-ion battery age and demonstrate a significant advance in the feasibility of potassium-ion based technologies.



Behind the Research

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Research Objectives

Working with the Advanced Battery Research Group at AIST, Dr Masese's research explores high performance next-generation rechargeable battery systems.

Detail

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Bio

Titus Masese hails from Kenya. He won a Japanese government scholarship after emerging amongst the top students in KCSE 2002 national examinations. He obtained his BEng, MSc and PhD degrees from Kyoto University (BEng supervisor: Prof Haruyuki Inui; PhD supervisor: Prof Yoshiharu Uchimoto). He is currently a researcher at AIST.

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Collaborators

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Personal Response

What are the next steps in your work to turn these honeycomb materials into a part of battery technologies?

From a fundamental point of view, we have shown that high voltages are attainable with the honeycomb-layered tellurate materials. Although tellurium has been studied intensively from both fundamental and technological perspectives, its use may render these honeycomb cathode materials unpractical. Part of our ongoing work is the design of tellurium-free related materials also demonstrating high voltages. While we note that there are other challenges that should ultimately be solved for the nascent potassium-ion technology to reach the market, the insights garnered in this study as well as other studies reported so far have identified many exciting and promising routes forward to designing a high-voltage battery prototype. We believe that by reaching out to the wide-spanning scientific community, we can bring the potassium-ion technology closer to reality.