Lithium-ion Battery Basic Knowledge

Lithium-ion battery

A **lithium-ion battery** or **Li-ion battery** (abbreviated as **LIB**) is a type of rechargeable battery in which lithium ions move from the negative electrode to the positive electrode during discharge and back when charging. Li-ion batteries use an intercalated lithium compound as one electrode material, compared to the metallic lithium used in a non-rechargeable lithium battery. The electrolyte, which allows for ionic movement, and the two electrodes are the constituent components of a lithium-ion battery cell.

Lithium-ion batteries are common in home electronics. They are one of the most popular types of rechargeable batteries for portable electronics, with a high energy density, tiny memory effect and low self-discharge. LIBs are also growing in popularity for military, battery electric vehicle and aerospace applications.

Chemistry, performance, cost and safety characteristics vary across LIB types. Handheld electronics mostly use LIBs based on lithium cobalt oxide ($LiCoO_2$), which offers high energy density, but presents safety risks, especially when damaged. Lithium iron phosphate ($LiFePO_4$), lithium ion manganese oxide battery ($LiMn_2O_4$, Li_2MnO_3, or LMO) and lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$ or NMC) offer lower energy density, but longer lives and less likelihood of unfortunate events in real world use, (e.g., fire, explosion, ...). Such batteries are widely used for electric tools, medical equipment, and other roles. NMC in particular is a leading contender for automotive applications. Lithium nickel cobalt aluminum oxide ($LiNiCoAlO_2$ or NCA) and lithium titanate ($Li_4Ti_5O_{12}$ or LTO) are specialty designs aimed at particular niche roles. The newer lithium–sulfur batteries promise the highest performance-to-weight ratio.

Lithium-ion batteries can pose unique safety hazards since they contain a flammable electrolyte and may be kept pressurized. An expert notes "If a battery cell is charged too quickly, it can cause a short circuit, leading to explosions and fires". Because of these risks, testing standards are more stringent than those for acid-electrolyte batteries, requiring both a broader range of test conditions and additional battery-specific tests. There have been battery-related recalls by some companies.

Research areas for lithium-ion batteries include life extension, energy density, safety, and cost reduction, among others. However, as both energy density and economy of scale have reached their maximum, the industrial attention along with the market demand is to increase the charging speed and drain current, while shelf and cycle at elevated temperature are also critical in real application.

Battery versus cell

International industry standards differentiate between a "cell" and a "battery". A "cell" is a basic electrochemical unit that contains the electrodes, separator, and electrolyte. A "battery" or "battery pack" is a collection of cells or cell assemblies which are ready for use, as it contains an appropriate housing, electrical interconnections, and possibly electronics to control and protect the cells from failure. ("Failure" in this case is used in the engineering sense and may include thermal runaway, fire, and explosion as well as more benign events such as loss of charge capacity.) In this regard, the simplest "battery" is a single cell.

For example, battery electric vehicles, may have a battery system of 400 V, made of many individual cells. The term "module" is often used, where a battery pack is made of modules, and modules are composed of individual cells.

Electrochemistry

The reactants in the electrochemical reactions in a lithium-ion battery are the negative and positive electrodes and the electrolyte providing a conductive medium for lithium ions to move between the electrodes. Electrical energy flows out from or in to the battery when electrons flow through an external circuit during discharge or charge, respectively.

Both electrodes allow lithium ions to move in and out of their structures with a process called *insertion* (*intercalation*) or *extraction* (*deintercalation*), respectively. During discharge, the (positive) lithium ions move from the negative electrode (usually graphite = "C_6" as below) to the positive electrode (forming a lithium compound) through the electrolyte while the electrons flow through the external circuit in the same direction. When the cell is charging, the reverse occurs with the lithium ions and electrons moved back into the negative electrode in a net higher energy state. The following equations exemplify the chemistry.

The positive (cathode) electrode half-reaction in the lithium-doped cobalt oxide substrate is:

$$\mathrm{CoO_2 + Li^+ + e^- \leftrightarrows LiCoO_2}$$

The negative (anode) electrode half-reaction for the graphite is:

$$LiC_6 \leftrightarrows C_6 + Li^+ + e^-$$

The full reaction (left: charged, right: discharged) being:

$$LiC_6 + CoO_2 \leftrightarrows C_6 + LiCoO_2$$

The overall reaction has its limits. Overdischarge supersaturates lithium cobalt oxide, leading to the production of lithium oxide, possibly by the following irreversible reaction:

$$Li^+ + e^- + LiCoO_2 \rightarrow Li_2O + CoO$$

Overcharge up to 5.2 volts leads to the synthesis of cobalt(IV) oxide, as evidenced by x-ray diffraction:

$$LiCoO_2 \rightarrow Li^+ + CoO_2 + e^-$$

Electrolytes

The cell voltages given in the Electrochemistry section are larger than the potential at which aqueous solutions will electrolyze.

Liquid electrolytes in lithium-ion batteries consist of lithium salts, such as $LiPF_6$, $LiBF_4$ or $LiClO_4$ in an organic solvent, such as ethylene carbonate, dimethyl carbonate, and diethyl carbonate. A liquid electrolyte acts as a conductive pathway for the movement of cautions passing from the negative to the positive electrodes during discharge. Typical conductivities of liquid electrolyte at room temperature (20°C (68°F)) are in the range of 10mS/cm, increasing by approximately 30–40% at 40°C (104°F) and decreasing slightly at 0 °C (32 °F).

The combination of linear and cyclic carbonates (e.g., ethylene carbonate (EC) and dimethyl carbonate (DMC)) offers high conductivity and SEI-forming ability. A mixture of a high ionic conductivity and low viscosity carbonate solvents is needed, because the two properties are mutually exclusive in a single material.

Organic solvents easily decompose on the negative electrodes during charge. When appropriate organic solvents are used as the electrolyte, the solvent decomposes on initial charging and forms a solid layer called the solid electrolyte interphase (SEI), which is electrically insulating yet provides significant ionic conductivity. The interphase prevents further decomposition of the electrolyte after the second charge. For example, ethylene carbonate is decomposed at a relatively high voltage, 0.7 V vs. lithium, and forms a dense and stable interface.

Composite electrolytes based on POE (poly(oxyethylene)) provide a relatively stable interface. It can be either solid (high molecular weight) and be applied in dry

Li-polymer cells, or liquid (low molecular weight) and be applied in regular Li-ion cells.

Room temperature ionic liquids (RTILs) are another approach to limiting the flammability and volatility of organic electrolytes

Charge and discharge

During discharge, lithium ions (Li^+) carry the current within the battery from the negative to the positive electrode, through the non-aqueous electrolyte and separator diaphragm.

During charging, an external electrical power source (the charging circuit) applies an over-voltage (a higher voltage than the battery produces, of the same polarity), forcing a charging current to flow **within the battery** from the positive to the negative electrode, i.e. in the reverse direction of a discharge current under normal conditions. The lithium ions then migrate from the positive to the negative electrode, where they become embedded in the porous electrode material in a process known as intercalation.

Procedure

The charging procedures for single Li-ion cells, and complete Li-ion batteries, are slightly different.

- A single Li-ion cell is charged in two stages:

1. Constant current (CC)
2. Constant Voltage (CV)

- A Li-ion battery (a set of Li-ion cells in series) is charged in three stages:

1. Constant current
2. Balance (not required once a battery is balanced)
3. Constant Voltage

During the **constant current** phase, the charger applies a constant current to the battery at a steadily increasing voltage, until the voltage limit per cell is reached.

During the **balance** phase, the charger reduces the charging current (or cycles the charging on and off to reduce the average current) while the state of charge of individual cells is brought to the same level by a balancing circuit, until the battery is balanced. Some fast chargers skip this stage. Some chargers accomplish the balance by charging each cell independently.

During the **constant voltage** phase, the charger applies a voltage equal to the maximum cell voltage times the number of cells in series to the battery, as the current gradually declines towards 0, until the current is below a set threshold of about 3% of initial constant charge current.

Periodic topping charge about once per 500 hours. Top charging is recommended to be initiated when voltage goes below 4.05 V/cell.

Failure to follow current and voltage limitations can result in an explosion.

Extreme temperatures

Charging temperature limits for Li-ion are stricter than the operating limits. Lithium-ion chemistry performs well at elevated temperatures but prolonged exposure to heat reduces battery life.

Li-ion batteries offer good charging performance at cooler temperatures and may even allow 'fast-charging' within a temperature range of 5 to 45°C (41 to 113°F). Charging should be performed within this temperature range. At temperatures from 0 to 5°C charging is possible, but the charge current should be reduced. During a low-temperature charge the slight temperature rise above ambient due to the internal cell resistance is beneficial. High temperatures during charging *may* lead to battery degradation and charging at temperatures above 45°C *will* degrade battery performance, whereas at lower temperatures the internal resistance of the battery may increase, resulting in slower charging and thus longer charging times.

Consumer-grade lithium-ion batteries should not be charged at temperatures below 0°C (32°F). Although a battery pack may appear to be charging normally, electroplating of metallic lithium can occur at the negative electrode during a subfreezing charge, and *may* not be removable even by repeated cycling. Most devices equipped with Li-ion batteries do not allow charging outside of 0–45°C for safety reasons, except for mobile phones that may allow some degree of charging when they detect an emergency call in progress.