Technical Notes

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Lithium-ion Battery Overview

This Technical Note compares several existing and emerging lithium-ion battery technologies and provides an overview of the safety issues involved in designing products with lithium-ion batteries.

The Information contained in this article builds on previous Technical Notes. See also: http://www.lightingafrica.org/resources/briefing-notes.html

Introduction

Lithium-ion (Li-ion) batteries are becoming more common in portable electronic devices due to their high energy density, lack of memory effect, and high charge and discharge rate capabilities. Li-ion batteries are a relatively new technology, first marketed in the early 1990s, and research and development work is ongoing to improve safety and increase capacity, charge/discharge rate, and lifetime. This technical note describes the types of Li-ion batteries currently on the market and briefly outlines charging methods and safety considerations.

Advantages and disadvantages

The main advantage of lithium-ion batteries is their high energy density. They have a long cycle life and do not suffer from the high self-discharge rate and memory effect of nickel-cadmium (NiCd) and nickel metal hydride (NiMH) batteries. Unlike sealed lead acid (SLA) and NiCd, Li-ion batteries do not contain toxic heavy metals.

The main disadvantage of Li-ion batteries is that they require careful attention to safety. Overcharging, overheating, or short-circuiting a charged Li-ion battery can result in fire or explosion. For a safe and long-lasting product, Li-ion-specific safety issues must be taken into account in product design.

Table A1 in the Appendix shows how the characteristics of Li-ion batteries compare to those of other common battery chemistries.

Types of Li-ion batteries

The term “lithium-ion battery” refers to a diverse family of battery chemistries. All Li-ion batteries use a process known as intercalation, in which lithium ions are incorporated into the structure of the electrode material. Lithium ions move from the positive to the negative electrode during charging and from the negative to the positive electrode as the battery is discharged.

Most types of Li-ion batteries available today differ in the composition of their positive electrode (cathode). New materials for the negative electrode are also being developed, but few of these are now available on the market. This section concentrates on the positive electrode material and briefly discusses negative electrode materials and construction techniques.

Positive electrode (cathode) materials

Different positive electrode materials vary in cost, safety, and energy density. Table 1 lists the types of positive electrode materials currently available on the market; Table A2 gives general characteristics of batteries made using these materials. Lithium cobalt oxide (LCO) is the most common type; nickel manganese cobalt (NMC) is somewhat safer and less expensive. Lithium iron phosphate (LFP or $LiFePO_4$) is emerging as a choice when safety or high discharge rate is more important than energy density, such as electric vehicles and power tools. Some cells use a blend of lithium manganese oxide (LMO) and NMC, which provides better cycle life and storage properties than either material alone.

Table 1. Properties of common positive electrode materials.[1]

Material	Chemical formula	Description
Lithium cobalt oxide (LCO)	$LiCoO_2$	Original commercial type; expensive raw materials
Nickel cobalt aluminum (NCA)	$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	Highest energy density per unit mass
Nickel manganese cobalt (NMC)	$LiNi_{1-x-y}Mn_xCo_yO_2$	Safer and less expensive than LCO
Lithium manganese oxide (LMO)	$LiMn_2O_4$	Safer and less expensive than LCO, but poor high temperature stability
Lithium iron phosphate (LFP)	$LiFePO_4$	Very safe, high power, but lower energy density. Best high-temperature stability

Negative electrode (anode) materials

Graphite is by far the most common material for the negative electrode, but some other technologies are under development. Lithium titanate ($Li_4Ti_5O_{12}$ offers very high cycle life, faster charging, and better safety than graphite, but at a cost of much lower energy density. These batteries are starting to become available commercially, mainly for electric vehicles and grid energy storage.[1] Table A2 gives general characteristics of batteries made using common positive and negative electrode materials.

Emerging lithium-ion technologies

Several new cathode materials are under development. "5V" materials like $LiNi_{0.5}Mn_{1.5}O_4$ support higher voltages and thus higher energy densities than current materials, which usually have a maximum charging voltage of 4.2 V (see Table A2). Alternative phosphate materials such as $LiMnPO_4$ may offer the advantages of $LiFePO_4$ while supporting voltages and thus energy densities comparable to or higher than those of other Li-ion chemistries.[2] Some of these new materials will require new electrolytes and other cell components able to withstand the higher voltages. Other new materials may improve charge capacity per unit mass by up to 35-40% relative to NCA.[1]

Anodes based on silicon or tin provide higher energy density than graphite but can be difficult to manufacture; some silicon- and tin-based cells are now on the market.[1] A few companies are attempting to bring nanostructured silicon anode materials to the market in the next two years; nanotechnology could also result in improvements to cathode materials.[3] Other nanotechnology research aims to improve safety and shelf life.

Cell construction

Like other batteries, Li-ion cells are available in rigid cylindrical and prismatic (rectangular) constructions. Also available are "polymer" or "pouch" cells, packaged in a flexible plastic pouch. These cells are sometimes called "lithium-polymer" (Li-Poly or LiPo), but the chemistry is the same as that of rigid Li-ion batteries.[1] Polymer cells can be made small and thin, making them common in portable music players and mobile phones.

Charging and Discharging Li-ion Batteries

Proper charge control and protection circuitry is critical for Li-ion batteries. Overcharging a Li-ion battery can lead to a fire or explosion, and overdischarging can permanently damage the battery. Many Li-ion batteries have built-in protection circuitry.

Li-ion batteries are usually charged in two steps (Figure 1). The first step is a constant-current charge at 0.5-1*C* until the battery reaches its maximum voltage, usually 4.1-4.2 V/cell. After the ending voltage is reached, the battery is charged at constant voltage until the current drops below a threshold, between 0.02*C* and 0.1*C*,[4,5] or for a fixed amount of time, around 2 hours.[4] If the battery is severely depleted, a slow charge (0.1*C*) is necessary to bring the voltage up to 2.5-3 V/cell[4,5] before the 0.5-1*C* charge can begin; however, attempting to charge a severely depleted battery may be unsafe, and the battery may have permanent capacity loss.[6]

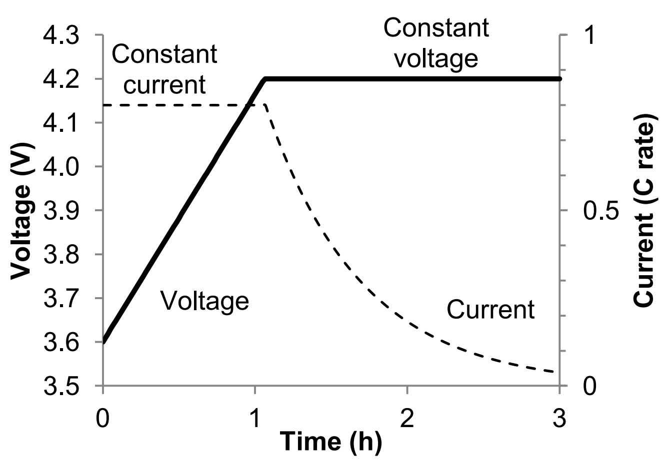

Figure 1: Approximate current and voltage during typical Li-ion charge cycle.[7] Exact values depend on charging conditions and battery type.

Li-ion batteries are not harmed by a partial charge; in fact, charging to a lower voltage will extend the cycle life of the battery, but with a significant capacity penalty. Charging a 4.2-volt battery to 4.1 V results in a 10% or larger reduction in capacity.[4,7] Accurate voltage regulation is critical for safely charging Li-ion batteries; the tolerance for overcharging can be 50 mV or less.[4,7] Charging cells in series requires circuitry to balance the voltage between cells so that no individual cell exceeds its maximum voltage.

C-rate terminology

Battery charging and discharging rates are often referred to in terms of *C*, the rate required to charge or discharge the battery in one hour. For example, for a 2.0 amp-hour battery, *C* is 2.0 amps, and 0.5*C*, also written *C*/2, is 1.0 amps. If the battery could be charged to 100% capacity at *C*/2, the charge would take approximately two hours. In practice, since the charge rate decreases during the constant-voltage phase, a full charge will take longer.

Most Li-ion batteries cannot be charged at ambient temperatures below 0°C or above 45-50°C. Charging at high temperature will decrease cycle life and may present a safety hazard; phosphate-based batteries may have somewhat better high-temperature performance than other Li-ion chemistries. Charging at low temperatures may lead to the growth of lithium metal dendrites, which can result in an internal short circuit, destroying the battery and potentially causing a fire. Ensuring that the temperature remains within the acceptable range is especially important for products that may be charged outdoors in direct sunlight.[8]

Unlike NiCd and NiMH cells, lithium ion batteries do not have a memory effect and do not benefit from full discharge cycles. Fully discharging a Li-ion battery will reduce its life, and discharging the battery below 2.5-3 V/cell can cause permanent damage[9] or short-circuiting.[10] Typically, the built-in electronics automatically disconnect the battery when this threshold is reached, rendering the battery pack unusable.[7]

Voltage and temperature limits vary from battery to battery. The voltage and temperature ranges in this technical note are general guidelines; the battery manufacturer's datasheets should be consulted for the limits that apply to specific battery models.

Safety

While all batteries can present safety hazards if used improperly, Li-ion batteries are especially sensitive to proper handling and treatment. Li-ion batteries can vent electrolyte, catch fire, or explode if overcharged, overheated, or short-circuited. Unlike the water-based electrolytes in SLA, NiCd, and NiMH batteries, Li-ion electrolytes use flammable organic solvents. Li-ion battery fires can be extinguished with water or standard dry chemical fire extinguishers.[11]

Many Li-ion batteries contain built-in protection circuitry to prevent dangerous conditions, as well as mechanical protection devices to prevent fire or explosion if the electronic protection fails. Batteries without these internal protection devices should not be used.

This section briefly describes the safety issues associated with lithium-ion batteries and provides an overview of international safety and quality standards that apply to these batteries.

Li-ion safety overview

- Use batteries that meet the UL 1642 or IEC 62133 safety standard and contain built-in protection circuitry.
- Do not allow batteries to be overcharged or deeply discharged.
- Use manufactured battery packs; do not combine packs or cells in series or parallel.
- Protect batteries from being crushed, punctured, or short-circuited.
- Get battery-specific information, including voltage, current, and temperature limits, from the battery manufacturer.

Overcharging

Overcharging is hazardous because the charged positive electrode material can begin to react with the electrolyte, resulting in electrolyte venting, smoke, fire, or explosion.[12] Some positive electrode materials are more stable—and thus safer—than others; LFP is the safest, followed by NMC, LMO, and LCO (the most common material). NCA is about as safe as LCO.[1]

The battery protection circuitry protects against overcharging by opening a switch if the voltage exceeds the limit. If the circuit fails and the battery continues to charge, a safety vent opens to release the pressure in the battery. The vent is designed to break the circuit when it opens, preventing further overcharging or overheating. Once the vent opens, the battery is destroyed.

Overdischarging

Deep discharge of Li-ion cells can lead to dissolution of the copper current collector on the cell anode; this copper can be deposited in the cathode and separator, possibly leading to a short circuit.[6] Overdischarging can also lead to capacity loss and swelling. Since many lighting products have electronics that consume a small amount of power even when the lamp is switched off, it is important to use battery packs with built-in electronics that disconnect cells before they are discharged to a potentially hazardous level.

Overheating

Overheating causes the negative electrode material to react with the electrolyte, causing venting or fire.[12] If the battery management system contains a temperature sensor in contact with the battery, it can stop charging before thermal runaway starts.

Short circuit

Short-circuiting a Li-ion battery can cause the battery to overheat, resulting in a fire. The risk of a short circuit can be reduced by good design, including separating or recessing battery terminals to prevent them from coming in contact with metal objects and ensuring that insulation on battery leads is in good condition. Li-ion batteries have built-in positive temperature coefficient (PTC) devices to prevent overcurrent and porous plastic "shutdown separators" which partially melt to stop the flow of current.

These safety devices are not always effective against internal short circuits, which can be caused by metal particles left inside the cells by faulty manufacturing. This type of defect caused a major recall of laptop computer batteries in 2006. A short circuit can also result from the cell being crushed or punctured.

Safety standards

Underwriters' Laboratories (UL) and the International Electrotechnical Commission (IEC) have published standards for safety testing of Li-ion batteries. Both the UL 1642 and IEC 62133 standards define a series of tests, including overcharge, crush, impact, and heating tests; to pass, batteries must not catch fire or explode, and in some cases must not leak or overheat. Neither standard includes an internal short-circuit test; this test has been proposed for a future version of IEC 62133.[1]

In addition to these standards, the Institute of Electrical and Electronics Engineers (IEEE) has published standards for batteries in portable computers (IEEE 1625) and cellular telephones (IEEE 1725); these standards specify additional design and manufacturing requirements, many of which are intended to prevent internal short-circuiting.

Air transport restrictions

International regulations established by the International Air Transport Association (IATA) and the International Civil Aviation Organization (ICAO) restrict the shipment by air of lithium-ion batteries. In general, small batteries contained within equipment are subject to fewer restrictions than large batteries or batteries packaged separately from equipment, as long as the batteries pass a series of safety tests defined in the UN Manual of Tests and Criteria (Part III, Subsection 38.3).

In the United States, there are additional restrictions for transport on passenger aircraft.[13] The cited IATA document provides a more detailed description of the regulations.

Shelf life

Like all batteries, Li-ion batteries will self-discharge during storage and must be periodically charged; the rate of self-discharge is generally about 2-10% per month. Most "self-discharge" is due to the current required to operate the monitoring electronics built into the battery pack.[14] The battery can be permanently damaged if allowed to discharge below the recommended minimum voltage.

Storage while fully charged will also reduce battery life, since the electrodes degrade faster when fully charged. To prevent this degradation while still allowing for some self-discharge in storage, many manufacturers recommend storing Li-ion batteries at 40-50% of charge capacity.[7,14] Storage at high temperatures also reduces battery life.

Under ideal conditions, if not allowed to self-discharge, a lithium-ion battery can last for five years or more.[7]

Disposal

The metals in lithium-ion batteries, including cobalt, nickel, manganese, iron, and aluminum, are not as toxic as the lead or cadmium in SLA or NiCd batteries; many governments allow their disposal in landfills. While Li-ion batteries can be recycled to recover metals, recycling is expensive, and the recycling infrastructure is not as widespread as that for lead-acid batteries. Charged lithium-ion batteries pose a fire or explosion hazard if crushed, punctured, or incinerated; batteries should be fully discharged before disposal.

Appendix: Comparison of performance characteristics

Table A1. Comparison of Li-ion (graphite anode) to other rechargeable battery chemistries.

Characteristic	$LiCoO_2$ (LCO)	$LiFePO_4$ (LFP)	SLA	NiCd	NiMH
Nominal voltage per cell	3.7	2.5-3.6[1]	2.0[15]	1.2[15]	1.2[15]
Specific energy (Wh/kg)	175-200[1,15]	60-110[1]	30-40[15,16]	35-80[15,16]	55-110[15,17]
Energy density (Wh/L)	400-640[1]	125-250[1]	50-90[15,16]	100-150[15,16]	160[16]-420[18]
Cycle life (to 80% original capacity at 100% DOD)	500+[1]	1000+[1]	200-300 (up to 400 at 80% DOD)[19]	300-1000[15]	500-1000[15]
Calendar life (years)	>5[1]	>5[1]	2-8[15]	5-7[15]	5-10[15]
Ambient temperature during charge (°C)	0-45[1]	0-45[1]	-40-50[15]	0-40[15]	0-40[15]
Ambient temperature during discharge (°C)	-20-60[1]	-30-60[1]	-40-60[15]	-20-70[15]	-20-65[15]
Self-discharge capacity loss per month	2-10%[15]	2-10%	4-8%[15]	15-20%[15]	15-30% (conv.)[15] 2% (advanced)[20]
Memory effect	No[1]	No[1]	No[15]	Yes[15]	Yes, less than NiCd[15]
Toxic metals	None	None	Lead	Cadmium	None
Battery management system required	Yes	Yes	No	No	No

Table A2. Typical properties of various Li-ion chemistries.[1]

Positive electrode	LCO and NCA	NMC	LMO		$LiFePO_4$
Negative electrode	**Graphite**	**Graphite**	**Graphite**	**Lithium titanate**	**Graphite**
Optimized for	**Energy**	**Energy or Power**	**Power**	**Cycle life**	**Power**
Operating voltage range	2.5-4.2 (rarely 4.35)	2.5-4.2 (rarely 4.35)	2.5-4.2	1.5-2.8	2.0-3.6
Nominal voltage	3.6-3.7	3.6-3.7[21]	3.7-3.8[21]	2.3	3.3
Specific energy (Wh/kg)	175-240 cyl 130-200 polymer	100-240	100-150	70	60-110
Energy density (Wh/L)	400-640 cyl 250-450 polymer	250-640	250-350	120	125-250
Discharge rate (continuous)	2-3*C*	2-3*C* (power cells >30*C*)	>30*C*	10*C*	10-125*C*
Cycle life (100% DOD to 80% capacity)	500+	500+	500+	4000+	1000+
Ambient temperature during charge (°C)	0-45	0-45	0-45	-20-45	0-45
Ambient temperature during discharge (°C)	-20-60	-20-60	-30-60	-30-60	-30-60

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