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The Birth of the Lithium-Ion Battery

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Throughout the 1980s, the development of portable electronic products such as video cameras, notebook computers, and cell phones led to a growing need for rechargeable batteries with greater capacity, or reduced size and weight for a given capacity. However, conventional rechargeable batteries such as lead–acid batteries and nickel–cadmium batteries, as well as nickel–metal hydride batteries, which were under development at the time, posed limitations to reduction in size and weight. Thus a need remained for a new, small, and lightweight rechargeable battery to be put into practical use.

The two main classifications for batteries are disposable (primary) and rechargeable (secondary), and batteries may also be classified by the type of electrolyte employed, either aqueous or nonaqueous. Some common battery types are shown in Figure 1 in accordance with these classifications. Aqueous-electrolyte batteries have a disadvantage in that the available voltage per cell is in principle limited to around 1.5 V, the voltage at which the water of the electrolyte begins to dissociate by electrolysis. Batteries that use an aqueous electrolyte thus face a natural limit in terms of capacity, which therefore restricts the scope for reduction of size and weight. On the other hand, nonaqueous-electrolyte batteries can obtain an electromotive force of 3 V or more per cell, offering much greater possibilities in terms of increasing capacity. An important example is the metallic lithium battery, a primary battery that was commercialized using a nonaqueous electrolyte and metallic lithium as the negative-electrode material.

	Aqueos electrolyte battery	Nonaqueos electrolyte battery (high voltage, capacity)
Primary battery (disposable)	Mn dry cell, Alkaline dry cell	Metallic lithium battery
Secondary battery (rechargeable)	Lead-acid battery, Nickel-cadmium battery, Nickel-metal hydride battery	**Lithium-ion battery**

Figure 1. Types of batteries.

Although attempts had been made to convert the metallic lithium battery into a secondary battery, even the best efforts could not succeed for two main reasons: 1) the tendency for lithium to precipitate on the negative electrode during charging, in the form of dendrites which easily cause short-circuiting; 2) the high chemical reactivity of metallic lithium which not only results in poor battery characteristics, including inadequate cycle durability because of side reactions, but also posed an inherent risk of a thermal runaway reaction, which was an insurmountable problem in terms of safety.

I focused on the creation of a practical new secondary battery with a nonaqueous electrolyte to meet the emerging need for a small and lightweight power source for portable electronics. I conceived the lithium-ion battery (LIB) in the early 1980s and completed a practical prototype in 1986 (priority patent application was filed in 1985.)[1] The resulting LIB is positioned as a nonaqueous-electrolyte secondary battery in Figure 1. The complete description of the lithium-ion battery is a "*nonaqueous secondary battery using transition-metal oxides containing lithium ion such as $LiCoO_2$ as a positive electrode and carbonaceous materials as a negative electrode.*"

The use of $LiCoO_2$ as a positive-electrode material was first reported by Goodenough and co-workers in 1979.[2,3] In 1982, Yazami and Touzain reported the world's first successful experiment demonstrating the electrochemical intercalation and release of lithium in graphite.[4,5] Although they used a solid electrolyte, this experiment provided the scientific basis for the use of graphite as negative-electrode material—as is standard in LIBs today.

In 1981 I started basic research on a nonaqueous secondary battery using polyacetylene as a negative electrode. Polyacetylene is an electric conductive polymer (Figure 2) discovered by Prof. Shirakawa, who received the Nobel Prize in Chemistry in 2000 for this work.[6] In 1983 I invented a new secondary battery using $LiCoO_2$ as the positive electrode and polyacetylene as the negative electrode.[7] The positive-

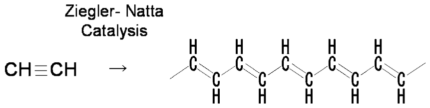

Figure 2. Structure of polyacetylene.

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Figure 3. The first test-tube cell (1983).

electrode material should be a transition-metal oxide containing lithium ion to provide the lithium ion for the negative electrode during charging. I confirmed the principle of this new secondary battery with an operational model in a sealed glass test tube (Figure 3). This test-tube cell functioned with the same cell reaction and operating principle as the lithium-ion battery as it exists today.

Although this cell was functional, the low real density of polyacetylene posed limitations on the available capacity, and the chemical stability of polyacetylene proved to be limited. I thus searched for a new carbonaceous material to use as the negative electrode. Although graphite had been studied as a negative-electrode material, it was known at that time that propylene carbonate, which was then the common organic electrolyte, would decompose during charging when graphite was used, and furthermore that the use of a solid electrolyte resulted in electrical resistance that was too high for practical charging and discharging. I therefore studied the suitability of several carbonaceous materials as the negative electrode. I found that carbonaceous material with a certain crystalline structure provided greater capacity without causing decomposition of the propylene carbonate electrolyte solvent as graphite did. The first example of the carbonaceous material with a certain crystalline structure was VGCF (vapor-phase-grown carbon fiber), which was reported by Oberlin, Endo, and Koyama in 1976 as a new carbon fiber for structural materials.[8]

The secondary battery which I successfully fabricated based on this new combination of component materials enabled stable charging and discharging, over many cycles for a long period. This new battery system comprising a "*non-aqueous secondary battery using transition-metal oxides containing lithium ion such as* $LiCoO_2$ *as a positive electrode and carbonaceous materials as a negative electrode*" was invented in 1985.[1] This is the present lithium ion battery.

The combination of electrode materials and the cell-reaction principle impart the LIB with the following characteristics.

1) Problems stemming from the high chemical reactivity of metallic lithium are avoided; these had inhibited the practical development of a nonaqueous-electrolyte secondary battery using metallic lithium for the negative electrode.
2) Lithium ions are supplied by the $LiCoO_2$ of the positive electrode and are transferred to the carbonaceous material of the negative electrode; this marks a new concept of a secondary battery.
3) An electromotive force of 4 V or more can be achieved along with a substantial improvement in energy density with the use of a nonaqueous electrolyte; this enables a significant reduction in size and weight as a secondary battery.
4) The cell reaction utilized is not a chemical transformation; this leads to stable battery characteristics over a long service life, including excellent cycle durability with little degradation by side reactions and excellent storage characteristics.
5) The battery production process is a simple and efficient production process; no special atmosphere is required for battery assembly, because $LiCoO_2$ is very stable in air although it contains lithium ions, and the negative electrode is composed of carbonaceous material which is also stable.

Next, I had to prove that this lithium-ion battery overcame the safety issues that had prevented commercialization of nonaqueous secondary batteries in the past. I carried out the world's first safety tests on lithium-ion batteries in 1986 (Figure 4). I knew that if the results of the tests were bad, the development would have to be terminated. Because of the risk of ignition or even explosion, I had to borrow a facility designed for testing explosives. In these tests an iron lump was dropped on to the batteries. The photograph in Figure 4c shows the test result with a metallic lithium battery: violent ignition occurred. Figure 4b shows the test result with a lithium-ion battery: ignition did not occur. This was a great relief, because if ignition had occurred in this test, the lithium-ion battery would not have been commercialized. This was the

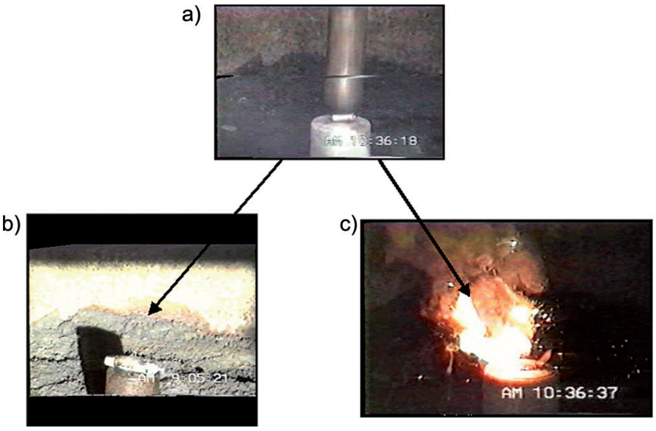

Figure 4. First safety tests with a lithium-ion battery in 1986. a) The moment an iron lump collides with a battery. b) Prototype lithium-ion battery after collision. c) Metallic lithium battery after collision.

Dr. Akira Yoshino was born in Suita, Osaka, Japan in 1948 and earned an MS in engineering in 1972 from the Department of Petroleum Chemistry at Kyoto University. In 1972, he joined the research division of Asahi Kasei Corporation, Kanagawa, Japan, where he conducted research on functional polymers and electronic materials. In 1981 he started research on secondary batteries. In 1985 he invented a new battery system C/$LiCoO_2$*, later named the lithium-ion battery. He also developed electrode fabrication methods using metal-foil current collectors as well as polyethylene separators, carbonate electrolytes, safety devices, and charging methods. He is now an Asahi Kasei Fellow and also serves as Adjunct Professor at Kyoto University.*

crucial turning point for the commercialization of the lithium-ion battery. I consider the success of these tests to be "*the moment when the lithium-ion battery was born*".

After further development, the lithium-ion battery was commercialized by SONY in 1991 and by a joint venture of Asahi Kasei and Toshiba in 1992. Commercialization of the lithium-ion battery made available an energy density of around twice that possible with nickel–cadmium or nickel–metal hydride batteries, in terms of both weight and volume. This facilitated a major reduction in the size and weight of the power supply for portable devices. Moreover, by providing an electromotive force of 4 V or more, the LIB made it possible to drive a cell phone with a single cell.

As shown in Figure 5, the use of the lithium-ion battery has expanded rapidly and it is forecasted to continue to increase. Applications classified as "consumer use" include portable devices such as video cameras, mobile computers, cell phones, and a variety of other electronic products with features and functions previously unavailable. With its high storage capacity, high current discharge, and excellent cycle durability, the lithium-ion battery is being used increasingly in electric-powered vehicles, whose adoption as an environmentally friendly mode of transportation is forecasted to grow sharply.

High-volume production of the lithium-ion battery and ongoing improvements to achieve greater performance have also driven many technological advances in the fields of carbonaceous materials, polymers, and ceramics, as well as progress in the related scientific disciplines of electrochemistry, surface chemistry, polymer chemistry, carbon chemistry, and ceramic chemistry.

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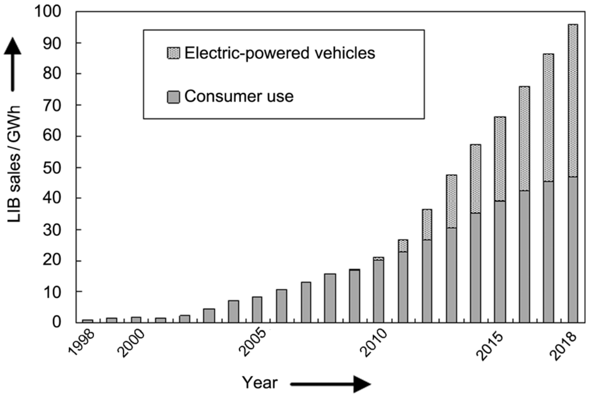

Figure 5. Forecasted expansion in demand for lithium-ion batteries. GWh = gigawatt hours.

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