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A123Systems

Professor Yet-Ming Chiang turned the corner from Commonwealth Avenue and entered the Boston University Photonics Center, taking the elevator to A123Systems' offices on the top floor. On this beautiful spring day in May 2003, the MIT campus, where this whole effort had started, offered an especially placid and dignified panorama of the other side of the Charles River. Less than a year since A123 had officially formed to commercialize a new lithium-ion battery technology developed in Chiang's research lab at MIT, the company was at a crossroads.

The young company, A123Systems, was founded on a revolutionary concept by which tiny particles (colloids) of the component materials would "self-assemble" into the battery structure consisting of a lithium electrolyte, cathode, and anode. Working prototypes of the battery had been promising enough to raise \$8.3M and launch A123Systems. The new technology relied on controlling the molecular forces between the powdered component materials to self-assemble the constituents on a scale 10 times smaller than the best assembly achievable using machines. The potential for safer, smaller, higher energy density batteries had prompted Chiang to take a one-year leave of absence from MIT to get the company started. Getting a battery to market with such radical technology could take years, but so far, things were going well.

Following its inception in February 2002, the A123 team had spent several months refining the colloidal self-assembly technology. Now a new opportunity had presented itself for the team to consider: As part of its licensing agreements with MIT, A123 had access to a new electrode material developed in Chiang's lab, an iron-based compound containing lithium that showed promise not only for the colloid self-assembly technology but also for conventional lithium-ion battery technology. The announcement of the new material in an academic journal, *Nature Materials*, had caught the attention of the business community.¹ Chiang and his management team had to decide whether to continue focusing on the original self-assembly concept or to propel A123 into the commercial world more quickly by incorporating the new electrode material into conventional, mechanically assembled lithium-ion batteries.

¹ *The New York Times* reference to the *Nature Materials* article noted that the new electrode material "offered advantages not only in terms of cost and power but in stability as well." See Anne Eisenberg, "What's Next," *The New York Times*, October 3, 2002, Sect. G, p. 5. Available from LexisNexis <http://www.lexisnexis.com>, accessed September 22, 2004.

Professors H. Kent Bowen of Harvard Business School and Kenneth P. Morse of MIT, and Douglas Cannon, PhD, prepared this case. HBS cases are developed solely as the basis for class discussion. Cases are not intended to serve as endorsements, sources of primary data, or illustrations of effective or ineffective management.

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New Battery Technologies for Portable Electronics

The evolution of rechargeable batteries accelerated as the world transitioned from devices and instruments constructed from bulky electrical components to those enabled by silicon microchip technology. Mobile devices (telecommunications, computers, entertainment, etc.) were being designed to require less power and lower voltages, making them easier to power by lightweight energy-storage systems. However, developing batteries for the rapidly evolving electronic-devices market was challenging. The theory underlying batteries was based on fundamental principles of thermodynamics; however, theory diverged markedly from practice in the manufacture of reliable and affordable batteries. This divergence created particular challenges for rechargeable batteries, in which the charging process reversed the chemical reaction to restore the reactants for discharge. Progress often occurred by arduous trial and error, including many blind alleys. The underlying science was still unsatisfactory for understanding and predicting actual occurrences at the interfaces between materials as chemical reactions between dissimilar materials drove the flow of electrons. Nevertheless, the scientific community was exhibiting new interest in developing this fundamental knowledge to further the search for better battery systems for the electronics industry, which was constantly developing more mobile products.

For many years, the nickel cadmium (NiCd) battery had been the only option for modern electronics. These batteries were a great improvement over carbon batteries, which had been the standard for decades. Later, the development of nickel metal hydride (NiMH) batteries greatly improved batteries' performance characteristics and quickly became the technology of choice. When lithium-ion batteries became available in 1990, offering higher energy densities comparable to the NiMH technology, the two battled for market share. The advantages of lithium eventually won out, making it the material of choice for portables requiring a small form factor (the amount of space in a device reserved for batteries).

The lithium-ion rechargeable battery offered advantages unavailable with any other battery chemistry. Lithium was the lightest of all metals, had the largest electrochemical potential,² and provided the greatest energy content per unit volume. In addition, lithium-ion batteries had no memory effect (hysteresis), and no scheduled cycling was needed to prolong battery life. The energy leakage rate of ~8% per month was less than half that of NiCd and NiMH batteries.³

Lithium compounds had been identified as potential electrode materials for rechargeable batteries in the early 1970s, but commercialization was difficult, in part due to safety issues. Metallic lithium explodes on contact with water, necessitating careful handling and packaging. By the mid 1980s, small nonrechargeable, button-sized lithium batteries were available, but most were classified as hazardous products. Sanyo and Matsushita (Panasonic) aggressively pursued rechargeable batteries using nickel, avoiding many of the safety concerns. However, lithium's potential for a high-energy-density, higher voltage battery cell made it an attractive option—if it could be handled safely.

In 1987 Sony began development of a lithium-based rechargeable battery. Recognizing that the right lithium compound would be difficult to find, the company simultaneously funded six separate research efforts, each pursuing a different combination of materials. This parallel approach required significant resources but minimized time lost pursuing any single unproductive path. Projects were

² *Electrochemical potential* is the electrical equivalent of a chemical reaction's energy, expressed as the equivalent voltage for the reaction. Thus, when the lithium contained in the cathode and anode of a lithium ion battery reacts, the electrical potential is 3.6 volts.

³ Isidor Buchman, "Will Lithium-Ion Batteries Power the New Millennium?" PowerPulse.Net, 2000. http://www.powerpulse.net/powerpulse/archive/pdf/aa_103000c.pdf, accessed September 9, 2004.

evaluated at monthly meetings to determine future directions, and finally one team found the right combination. The safety problem was solved by using a special alloy consisting of oxides of lithium and cobalt for the cathode, and a form of carbon as the lithium storage material for the anode. This combination of materials was not as reactive as a metallic lithium-based battery, but still worked well. The oxide alloy also had the unique characteristic that lithium ions could be cycled in and out of the material 1000 times—enough cycles to be usable for rechargeable batteries.⁴

Sony's product announcement came in February 1990; mass production of lithium-ion batteries began the following year. Panasonic and Sanyo quickly developed similar lithium-ion battery technologies that were on the market by 1994.

Lithium-Ion Battery Technology⁵

A typical lithium-ion battery contained many cells (sandwiches) consisting of an aluminum current collector covered with a layer of the lithium-cobalt oxide cathode, a polymer film separator, and a copper current collector (anode) covered with a graphitic carbon material (see **Exhibit 2** for a cross-sectional view of a cylindrical Li-ion cell). The entire assembly was infused with a nonaqueous liquid electrolyte in what was known as a "flooded cell" construction. As a lithium ion moved through the electrolyte that separated the anode and cathode, an electron took a different path through the current collectors and electronic device it was powering. Anode and cathode materials were good electron conductors in order to not constrict the flow of electrical current. In addition, these materials allowed the easy flow of lithium ions in and out of their crystal structures. The polymer material, saturated with the electrolyte that separated the cathode and anode, was designed to have a low resistance to the flow of lithium ions and a very high resistance to the flow of electrons.

The first lithium-ion batteries marketed by Sony used as a cathode material LiCoO_2 , which was still widely used in 2003. Derivative materials consisted of alloys in which some of the cobalt was replaced by nickel or manganese.⁶

Sony's first anodes utilized a form of petroleum coke, but carbon with a graphite structure became the anode material of choice because lithium could be stored easily ("intercalated") and subsequently removed from the space between carbon layers. Over time, many types of carbon materials became available.

Polymer films isolating the anode and cathode were typically microporous polyolefin materials with channels for lithium ions to move back and forth during charging and discharging of the battery. By 2001 the thickness of the separator had been reduced to about $15\mu\text{m}$, about one third the thickness of a human hair. Cathode layers (aluminum foil coated with the oxide) had a total thickness of about $180\mu\text{m}$, while anode layers (copper foil coated with a carbon-based material containing lithium) were about $200\mu\text{m}$ thick. The cathode, separator (electrolyte), and anode layers were sandwiched together and wound to form the battery.

⁴Sony Corporation, "Safe, Powerful and Long-Lasting," Sony Corporation global website,, <http://www.sony.net/Fun/SH/1-24/h3.html>, accessed September 9, 2004.

⁵ Grant M. Ehrlich, "Lithium-ion Batteries," *Handbook of Batteries*, third edition, David Linden and Thomas B. Reddy (New York, NY: McGraw-Hill, 2002), pp. 35.1.

⁶ The original patents for these cathode materials were issued to John Goodenough and his colleagues at the University of Texas and referred to a specific crystal structure. See U.S. Patents 4,357,215 and 4,302,518.

Chiang related the current state of battery technology to the original concept developed by Alessandro Volta two centuries ago:

One of the interesting observations about battery design and construction is that we still use a laminated construction, which is what Volta's original paper in the year 1800 shows (see **Exhibits 3 and 4**, showing laminated technology and the cells they produce). That layered design created a manufacturing issue. Lithium-ion batteries require thinner layers for higher discharge rates and greater utilization of the active materials—the available stored energy. And for cost reasons, physical assembly rather than any thin film deposition process is still used. This fabrication and assembly process has been pushed pretty much to its limits.

Big advances in a mature technology like batteries were hard to find. Most advances were incremental in nature, either finding slightly better materials or thinning the layers to improve performance.

By 2003, the worldwide market for rechargeable batteries had reached \$5.2 billion, with lithium-ion batteries accounting for 73% of the market.⁷ Lithium-ion batteries accounted for 90% of the batteries in laptop computers, cell phones, and camcorders, and were making inroads into portable games and audio players, as well as cordless power tools. Approximately two-thirds of the manufacturing was done in Japan, but that number was expected to decrease as more production shifted to China. Eleven companies were shipping at least one million batteries each per month. Sanyo and Sony were the clear leaders, shipping 34 million and 21 million batteries per month, respectively.

The market was very competitive, and larger manufacturers benefited from economies of scale. In fact, only the three largest manufacturers were making significant profits. Extreme pricing pressure from buyers and competition from suppliers had slashed the price of a battery from nearly \$6 in 2000 to about \$2.50 by the end of 2003. Meanwhile, battery performance had improved almost 10% annually over the same period.

Chiang's Research Lab at MIT

Chiang directed a research group at MIT that was medium-sized by academic standards (12-15 researchers). Members of the group ranged in educational level from postdoctoral associates to undergraduates. The lab typically included three or four postdocs, each of whom would spend one to three years at MIT before leaving for positions in academia or industry, and six to ten graduate students who were working toward master's or Ph.D. degrees. At any given time, several undergraduate students were also engaged in research to fulfill their thesis requirement or as part of MIT's innovative Undergraduate Research Opportunities Program (UROP), under which Chiang had gotten his own start in research. The Chiang laboratory focused on the design, synthesis, and characterization of advanced inorganic materials, and also on devices and technologies enabled by such materials. In particular, Chiang had directed his group's efforts over the preceding decade toward electromechanically and electrochemically "active" materials—namely, materials capable of converting electrical energy to mechanical work, or chemical energy to electrical work. For example, at the same time the new lithium-ion battery was being developed, another major research program was underway in which new compositions were being invented and processes developed to grow single-crystal fibers of piezoelectric materials, in which an applied voltage resulted in shape change that could be used to create deformable structures. The vision behind this technology, supported

⁷ These numbers do not include conventional batteries such as the lead-acid batteries used in automobiles.

primarily by DARPA⁸, was to create fiber-reinforced composites in which the fibers acted as artificial muscles to enable such applications as human exoskeletons or shape-morphing aircraft. Cross-pollination between the various research projects was common. Physically, Chiang's laboratory was a warren of eight separate rooms spread across the fourth floor of a 1960s-era building at MIT. Adhering to a principle of flexibility and adaptability, the lab boasted relatively few "centerpieces"; most of the lab was a mix of state-of-the-art characterization tools such as an atomic force microscope and instruments for precisely measuring piezoelectric strain or electrochemical behavior, combined with processing equipment ranging from a bank of freeze-driers for powder synthesis to a high-temperature, single-crystal-fiber-pulling machine. Befitting a laboratory with origins in ceramic materials, approximately 30 high-temperature furnaces were sprinkled throughout, capable of firing samples at temperatures ranging from 300 to 2400 degrees centigrade.

A Revolutionary Battery Concept: Self-Organizing Materials

Chiang's research group began researching better lithium cathode materials in the mid-1990s. In early 2000 Chiang began wondering if there might be a new way to push the thickness limitations of battery cells. What if battery layers could form themselves? Chiang had collaborated for years with Roger French, a DuPont researcher and professor of materials science at the University of Pennsylvania.⁹ Chiang commented on their relationship, "He and I have continued collaborative research on surface forces over these many years. One of the things that we both have been interested in is the Hamaker constant for different materials."

The Hamaker constant was a measure of the strength of the van der Waals force between materials. This force was significant only for very small particles—a micron or less in size.¹⁰ The force originated in the momentary non-uniform distribution of electrons in the atoms constituting a particle. As a result of the consequent polarization, a weakly attractive or repulsive force existed for any nearby particle. A large positive Hamaker constant indicated that two particles were strongly attracted to each other; a small value indicated weak attraction. The value of the Hamaker constant also depended on the medium in which the two particles were embedded.

Chiang described how this fundamental property of matter related to the challenge of revolutionizing battery technology:

With the right combination of materials, the Hamaker constant can have some very interesting properties. And one of these curiosities is the fact that the Hamaker constant can actually have a negative value and therefore cause two materials (particles) to repel each other if you immerse them in the right medium... And so we discovered and designed materials systems that organized themselves into an electrolyte separator between the anode and the cathode. This basic concept about materials was a key part of a self-organizing colloid concept.

Basic research rooted in years of studying the properties of materials and colloids led Chiang to the fundamental idea that he could tailor the forces between materials constituting the battery, deriving a self-assembly process to make a practical battery on a dimensional scale never before possible. Negative Hamaker constants had been a scientific curiosity with no real practical

⁸ The Defense Advanced Research Projects Agency (DARPA) was legendary as the funding source for breakthrough science and technologies at U.S. universities and research institutes, being credited with having created many of the computer and networking technologies as well as the science underlying the disciplines of computer science and materials science.

⁹ French and Chiang had been friends since graduate school at MIT.

¹⁰ A micron, or micrometer, is one-millionth of a meter. Small particles suspended in a liquid were called *colloids*.

applications. The concept of a self-organizing battery system required mutually attracting cathode particles and mutually attracting anode particles with the constraint that the cathode particles repelled the anode particles, all in the presence of a third material that became the electrolyte separator. The production concept involved suspending carefully designed cathode and anode particles in a solution of the third material, whose molecular forces would first force the individual particles to separate and then “self-assemble” to form independent, three-dimensional, interconnected structures of the cathode, separator, and anode.¹¹ The thickness of the separator layer could be as small as a few molecules and resulting batteries could be fabricated in any shape or size.

The most difficult part of the invention was finding materials with negative Hamaker constants to give a repulsive force. Chiang summarized this challenge: “The Hamaker constant is determined by another fundamental property, the material’s refractive index. If you have a system consisting of three materials in which the numerical value of each material’s refractive index varies monotonically in the order 1, 2, 3, then material 1 will repel material 3.¹²” To self-assemble a battery required a separator material 2 with an index of refraction between those of the cathode and anode materials¹³ (see **Exhibit 5**, a schematic of the structure).

Designing a system of battery materials with a negative Hamaker constant between anode and cathode materials turned out to be very difficult. The existing theoretical models relating the index of refraction to the Hamaker constant weren’t good enough to guide this search. Fortunately, Chiang’s friend Roger French had been working to advance the theory and physical characterization of the way light interacted with materials. Chiang described the background research:

Roger was able to develop a methodology for calculating the Hamaker constant from directly measured optical response over a very wide frequency range. What you’d really like to do is to take account of interactions at every frequency. However, this requires large amounts of optical data. We needed an approximation, but a realistic one. Most of the earlier approximations used data that was easily available, and even though widely used, it turned out to not be very accurate.

Our research at MIT was an investment of several years finding the right materials. This was the hardest part: discovering a low-index material and a high-index material with other key characteristics. In addition to the right optical characteristics, both anode and cathode materials must conduct electrons; both must be lithium-ion hosts.

Development of the Self-Assembling Materials System

Conventional lithium-ion anode and cathode materials did not have the right properties for self-assembly, so Chiang’s team had to develop them based on the new theoretical framework. They studied lithium-iron phosphate, which offered the required characteristics with respect to lithium-ion flow in and out of the structure but was basically an electrical insulator and would not work as a cathode. It did, however, have two important advantages over lithium-cobalt oxide: it was about one-fourth the cost and was much safer in that it was not so chemically reactive in the charged state.

¹¹ The volume fraction of particles necessary to form a three-dimensional structure was determined mathematically from percolation theory.

¹² The symbol for the Hamaker constant is A . The name of the company, A123, was chosen to reflect this unique monotonic increase for the three constituents of the self-assembled battery.

¹³ The index of refraction of a material is defined as the speed at which light travels through the material compared with the speed of light traveling through a vacuum. While light at different frequencies travels at the same speed in a vacuum, it may have different speeds at different frequencies in a given material.

In rare instances, batteries with lithium-cobalt cathodes had caused fires or explosions. Most importantly, lithium-iron phosphate had the right optical properties. Chiang believed the electrical conduction deficiency could be resolved later.¹⁴

Graphite, the cathode material used in commercial lithium batteries, was adaptable for self-assembly as it was a high-index material. Methylene iodide had an intermediate index of refraction and served as the liquid dispersant for the anode and cathode particles. Polystyrene was added to the liquid and became the polymer binder when the suspension was dried. Based on Chiang's theory, the methylene iodide, lithium perchlorate (the source of lithium ions in the electrolyte), polystyrene, graphite particles, and lithium-iron phosphate particles could all be mixed as a dispersion and poured into a mold. After the methylene iodide evaporated, the three-dimensional battery structure would remain.

The final problem required separate electrical contacts to the cathode and anode particle networks for the positive and negative battery electrodes. All metals have high indices of refraction and would easily attract the graphite anode network. Because of its electrochemical stability, copper was the ideal candidate for the anode current collector.

Connecting to the cathode particle network was not so easy. Chiang's student, Doug Moorehead, discovered the solution as part of his thesis work. He discovered that aluminum, which is light and cheap, could be coated with a special conducting polymer that also had a low index of refraction. The low index of refraction caused it to preferentially attract the lithium-iron phosphate particles, which also had a low index of refraction.

Despite the many obstacles and seemingly contradictory requirements for the battery materials, the concept looked promising. After extensive testing of hypotheses and materials, primitive devices were fabricated in the summer of 2001. These batteries demonstrated that the electrochemical cell had the predicted voltage and could be charged and discharged. The self-assembly battery concept looked very promising.¹⁵

Creating an Early-Stage Company

Ric Fulop, a serial entrepreneur with a legendary Rolodex, had been involved in five startups by the time he was 27 years of age and was looking for an idea to start yet another company. Howard Anderson, founder of the venture capital (VC) firm YankeeTek and lecturer in the MIT Sloan School, had funded two of Fulop's previous ventures and given him office space to be an "entrepreneur in residence" while he looked for his next activity. Despite losing close to \$10M on Fulop's previous two ventures, Anderson decided to take another bet on Fulop: "People would have probably said, 'Boy, this guy is stupid investing again,' but Ric has a certain genius. His genius is that he sees how things might be put together and how technologies not intended for one use may be used for another application. I know very few people in my venture capital career that can do that, and he is one of them."

¹⁴ Materials represented the largest element of the battery cost, and the cobalt-based compound was about four times more costly than that projected for the iron-phosphate material.

¹⁵ The research required to discover these materials and tailor them to self-assemble required not only a good theoretical framework, but also sophisticated experimental techniques including, for example, an Atomic Force Microscope which could actually measure the microscopic attractive and repulsive forces between particles.

Fulop had decided he wanted to start a company around a technology that had high barriers to entry, something he hadn't enjoyed in his last venture that deployed networking equipment. From a market standpoint, energy businesses looked attractive. He spent six months looking at the market and traveled around the country, visiting several universities. Portable fuel cells and portable batteries attracted his attention, and after meeting with researchers in the field, he decided batteries were the best bet. Fuel cells were still too big for portable devices and had an additional barrier for consumers. "You had to convince them that they had to put fuel into a portable device, which I didn't think was an easy proposition."

Once he focused on the battery industry, his search was short. "There aren't a lot of leading-edge scientists in the field, and there aren't a lot of breakthroughs. It's an industry that over the past decade has been growing at 10% per year with not a lot of new production capacity. And lithium-ion technology had changed little since its initial introduction by Sony. So I thought there was potential for a breakthrough; something was in the universities that I could utilize and build a company around."

Fulop had heard about Chiang's battery work and stopped by his office one day in early 2001. "Hi, I'm Ric Fulop. I want to start a battery company. What do you think about carbon nanotubes for batteries?"

Chiang's response was, "I think that's a terrible idea. You might be able to use nanotubes for something in a battery, but I don't think it's going to be the revolutionary concept. But I've been working on another project that I think has commercial potential."

Fulop was excited by the self-organizing battery concept. "And the opportunity for a battery with four times the energy density of the available lithium-ion technology [that] could be recharged 100 times faster. So that's big. That's a huge value proposition."

They continued talking and decided the new venture would be an early-stage company dedicated to further development of the self-assembly battery. Thus, their first task was to identify the research and development leader for the company. Chiang had co-founded American Superconductor in 1987 and brought Bart Riley into the company. Riley had spent eleven years there, and as close friends and fellow materials scientists, they frequently discussed ideas that might or might not have start-up potential. Chiang knew the contributions Riley could make to the start-up, so Riley became a member of the founding team.

Chiang recalled: "So we ended up getting the company off the ground around this concept. And in 2001 I spent most of the summer making the rounds of the venture community with Ric and Bart. We visited about thirty firms and got very good at the pitch."

Intellectual Property Rights?

Concurrently to seeking VC funding, the A123 team negotiated with MIT's Technology Licensing Office an exclusive license to the key patent filings from Chiang's laboratory. Chiang excluded himself from these negotiations, consistent with MIT's "rules of engagement" for faculty involved in outside professional activities. MIT had clear guidelines and policies, developed over time and from experience, that were designed to avoid conflicts-of-interest and protect the integrity of the research and educational enterprise. Fortunately, Ric and Bart both understood the licensing process from their prior experiences, and the terms of the license were negotiated smoothly.

The A123 team put together a first round of financing of \$8.3M in December 2002, led by Northbridge Ventures along with Sequoia, Sparta Group, YankeeTek, and MIT's own venture fund.

Four months later, an additional \$4M was raised from corporate investors Motorola and Qualcomm, who represented superb technology companies and large users of lithium-ion batteries. Howard Anderson saw these corporate investments as an initial validation of the concept. "If Motorola passes on it and says it's good, everyone pretty much accepts it."

Richard Holman, a freshly minted MIT Ph.D., was the first senior technical hire. He had a strong background in materials processing and wanted to try his hand at a start-up. His thesis advisor recommended him. After a few meetings with Chiang and Riley, now the vice president of R&D, he was brought on board. Holman recalled his initial excitement when learning about the technology: "My original impression was, 'WOW! This is the kind of thing that is entirely novel.' This is what is great about so many start-ups. It's a completely new idea, the kind of thing nobody's ever thought of."

During his first two months, he was charged with the technology transfer: "learning the techniques and chemistries and what-not" at MIT.

A home for the new company was found in the Photonics Business Accelerator in the Boston University Photonics Center. The \$85 million facility has 10 floors totaling 235,000 square feet of space housing state-of-the-art research laboratories, classrooms, offices, and business accelerator space. The Photonics Business Accelerator comprised one floor of the building and could flexibly house up to fourteen startup companies. Companies shared access to a variety of laboratories and equipment, and benefited from an existing physical plant infrastructure.

The match between the center and A123's needs was immediately apparent to Holman: "The great thing about this site is the labs. We have full access to fully furnished labs: wet labs, hoods, and everything. We have access to equipment like SEM [scanning electron microscopy], AFM [atomic force microscopy], FTIR [Fourier transform infrared spectroscopy], and other equipment that we are charged student rates for because we're part of the community. And there's the access to MIT, which is important when we're in such close collaboration."

The young company moved into the Photonics Center in March 2002 with fewer than 10 people. Chiang described the situation: "We formed this company, we had our funding, and we got a very good team including a number of good colloid scientists, very experienced battery people, and relatively few fresh-out-of-MIT types. And so we plugged away at this problem over the course of a year."

Digging In, Hitting Rocks

The initial results were "so promising, so quick," the team expected to have a product to pilot scale within months. As the technology transfer from MIT to A123 progressed, however, it became apparent that development might be more involved than originally thought. Holman remembered: "The first half of the technology transfer is learning the stuff there [MIT]; the hard part is you have to reproduce it here [A123]. And that was hard. And that's when it started to become clear that this system wasn't fully worked out, and there was still a lot of work to be done."

Several problems needed to be solved to take the self-assembled battery from idea to reality. First, A123 had to find a new cathode material or modify a known material to achieve the required Hamaker constant. Also, a practical binder and electrolyte had yet to be discovered. The reality of self-assembly batteries became a nightmare. Holman described the realities of bringing science from the lab to practice:

Over a period of time, we tried things and started to see how difficult it was, moving from concept to real batteries. Because management isn't there every day, they don't gain the insight that you gain, and they don't understand just how difficult it is. It starts to dawn on everyone – boy, this is really hard and it's going to take a long time to make this happen. There is still so much we don't understand.

Another Technology Development at MIT

Meanwhile, research on lithium-iron phosphate in Chiang's lab at MIT continued to evolve. The material's optical properties made it a promising cathode material for a self-organizing system, but it was intrinsically an electrical insulator. Fortunately, about the time A123Systems was formed, Chiang assigned to a post-doc the task of turning the insulator into a conductor. After several months' work, the post-doc discovered that by adding about 1% of a metal such as zirconium, titanium, or niobium, the conductivity increased by eight orders of magnitude—100 million times! A paper describing the results was published in *Nature Materials*, generating quite a stir in the battery industry. It also caught the attention of a *New York Times* reporter.

Lithium-iron phosphate was quickly recognized as a promising potential replacement for the cathodes in conventional lithium-ion batteries. It was much more stable than the lithium cobalt oxide currently used, would eliminate most of the safety concerns associated with lithium-ion batteries, had cost advantages, and could be charged or discharged efficiently in just a few minutes.¹⁶

Four months after the paper's publication in *Nature Materials*, the initial hype had not abated. Established battery companies continued to call for samples and to learn more about the new material's potential. The A123 management team was concerned that the publicity was distracting their staff from the development of a self-assembled battery, yet some of the technical staff wanted to develop the new cathode. The company was clearly divided about how best to use its precious resources.

Some saw the impetus to develop a new cathode as simply the "grass is always greener" syndrome; others viewed it as a logical reaction to a real opportunity. Richard Holman observed that "maybe this isn't the home run that the self-assembly will be—if we can ever make it work—but this could fund the company for many years, and it could be a huge success. There's got to be applications for a material that has these properties."

The A123 team's first results with lithium-iron phosphate had been on very small-scale samples in the lab. Doubts remained about whether the material could be scaled up. Would it behave the same? Larger samples and more tests followed. More and more data came in to confirm the original results. Scaling up the process would take months, but it looked much more straightforward than making the self-assembled battery a commercial process. Once fully developed, the new cathode material was largely a "drop-in" to existing battery technology. It looked like a product.

¹⁶ Industry experts estimated that a lithium-ion battery which sold for \$2.50 contained materials that cost \$1.50. The most costly component was the lithium-cobalt cathode material at about \$0.70 per battery. The gross margins of battery producers in Korean and Japan were estimated to be 33%, while in China they were about 50%.

Moving Forward

As Chiang and his partners looked out across the river to the MIT campus where this all had begun, they pondered the options available to A123, including the risks and business potential of different options, and the time and resources these would require.

They had already invested nearly a year since the company's inception to the development of the self-assembly battery technology, and if they managed to pull that off, it would be a big win. Besides, bringing something revolutionary to the battery industry would be very satisfying. Things were going relatively well, but commercialization was more involved than they had originally envisioned. With twenty employees they would need another round of funding within a couple of years. How long and how much total funding would be needed to get the product to market?

The advancement in the lithium-iron phosphate material was getting significant attention from established battery companies. A123 could probably have the material ready for commercial products within a year, but they would have to make sure that it became the standard. Partnering with an established company was certainly an option, and might help to gain industry acceptance and speed development. If A123 focused on producing the new cathode material, would they want to be a supplier of the new material to others, or actually make battery cells themselves? Alternatively, A123 could license the technology for the new material to another company, collect revenue, and not lose their focus. A win in the short run with the new material could make the company profitable and provide funding to finish the self-organized battery.

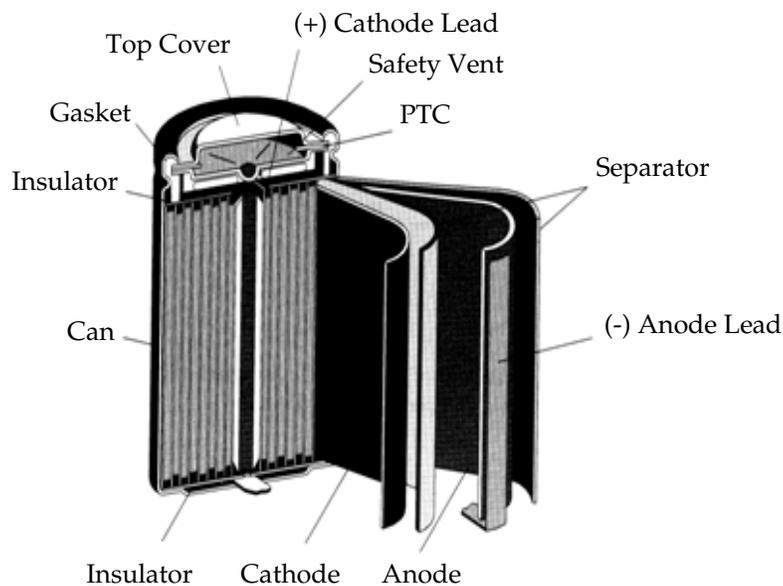
A decision needed to be made. The current self-assembly work was already stretching the company's resources, and adding the cathode development could slow them down on what was already a long-term project. Still, the new material did have real potential and could bring the company a product within a year or two. The right path was not clear-cut. Chiang and his partners¹⁷ could no longer delay their decision.

¹⁷ The management team consisted of Desh Deshpande (Chairman), David Vieau (President & CEO), Ric Fulop (Founder and VP Business Development), Bart Riley (Founder and VP Research and Development), Prof. Yet-Ming Chiang (Founder and Chief Scientist).

Exhibit 1 Lithium-Ion Batteries Shipped (million cells/month)

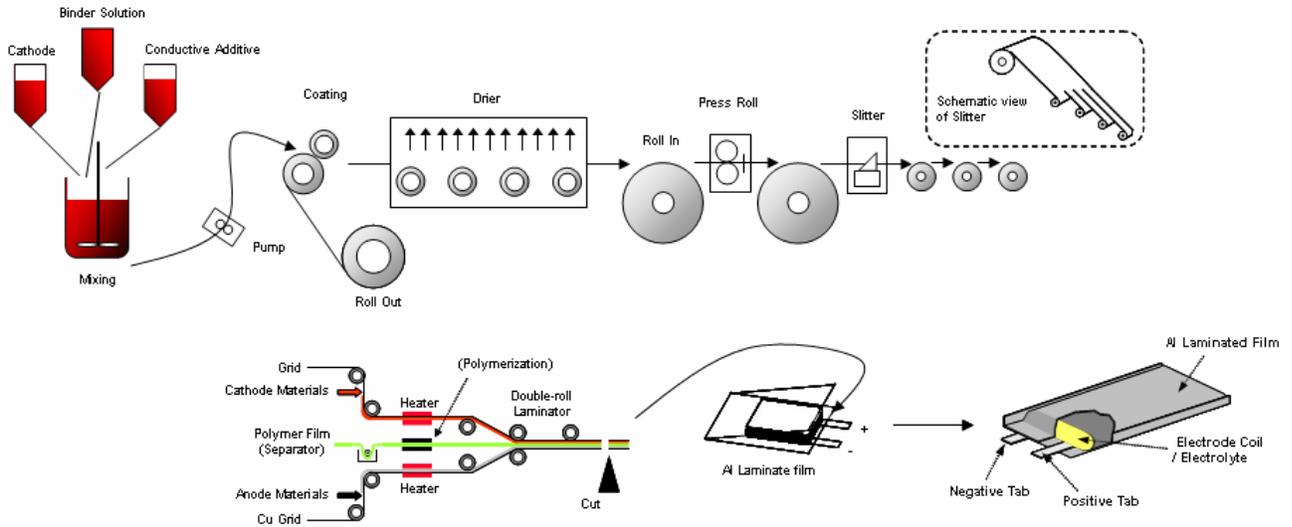
Company	2001	2002	2003
Sony	8.5	14	20
ATB	4	5	5
MBI	7.5	8	9
SANYO	13	17	27
GSMT	4	5	6
NEC	2	2	3.5
Maxell	1.5	2	3.5
BYD	4	7.5	11.5
LG Chem	1	3	6
SDI	2	5	7.5

Source: Company documents.

Exhibit 2 Lithium-Ion Battery Construction

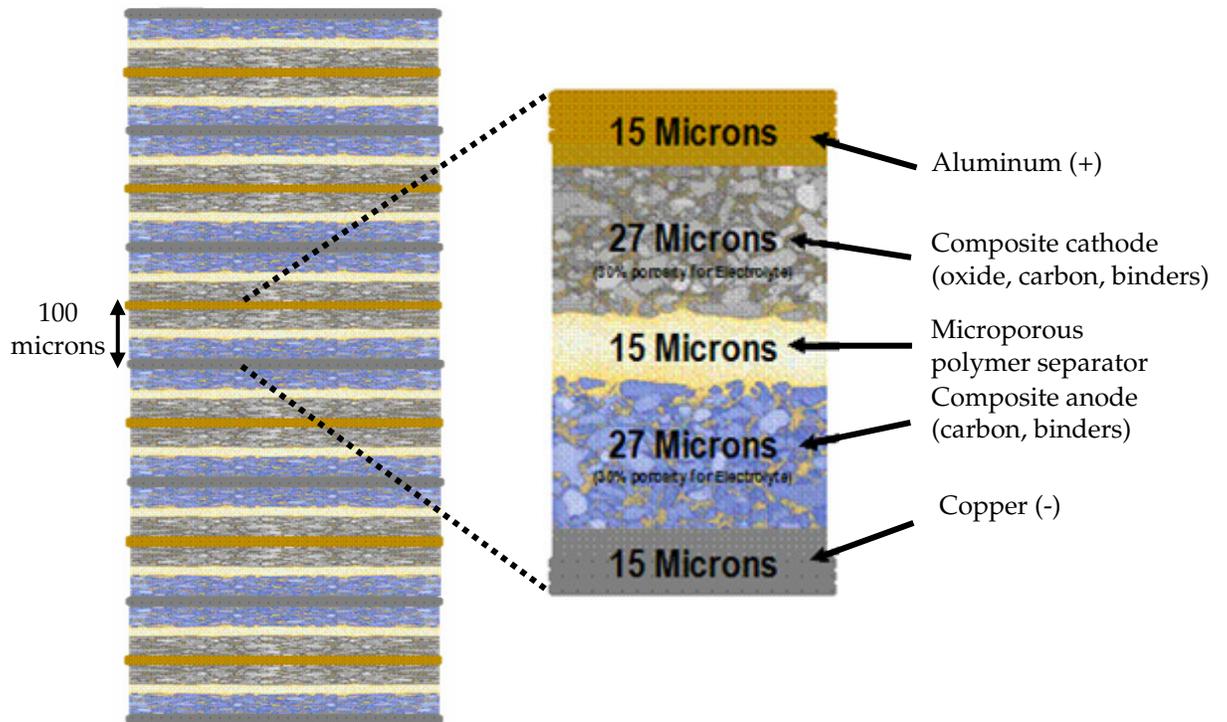
Source: Adapted from David Linden and Thomas B. Reddy, *Handbook of Batteries* (New York, NY: McGraw-Hill Companies, Inc., 2001), p. 35.32. (ISBN 0-07-135978-8)

Exhibit 3 Conventional Lithium-Ion Battery Construction



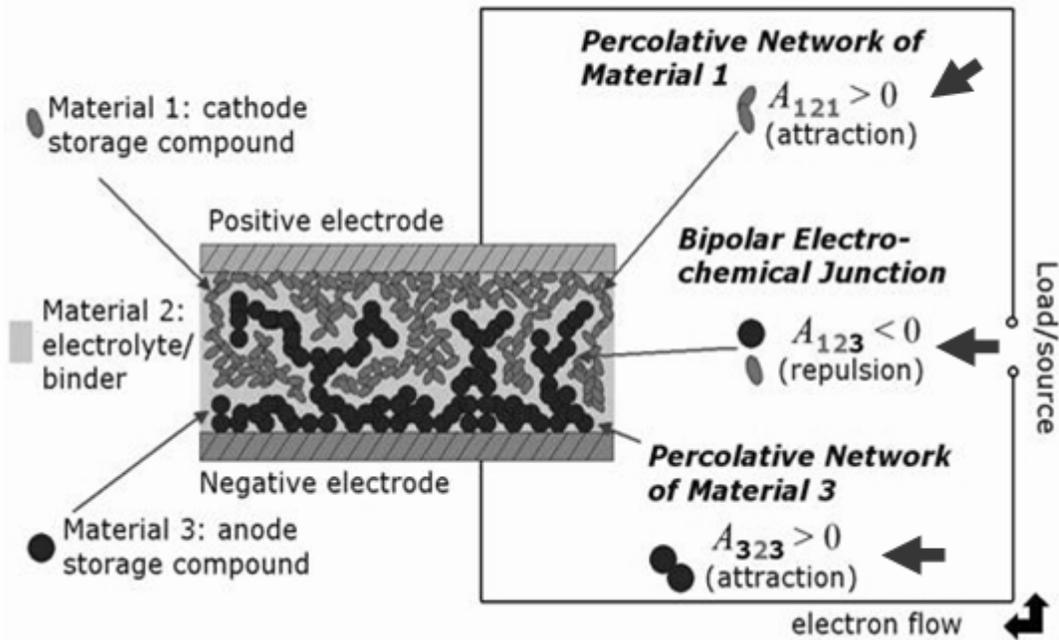
Source: Ric Pulop.

Exhibit 4 Cell Produced Using Laminated Technology



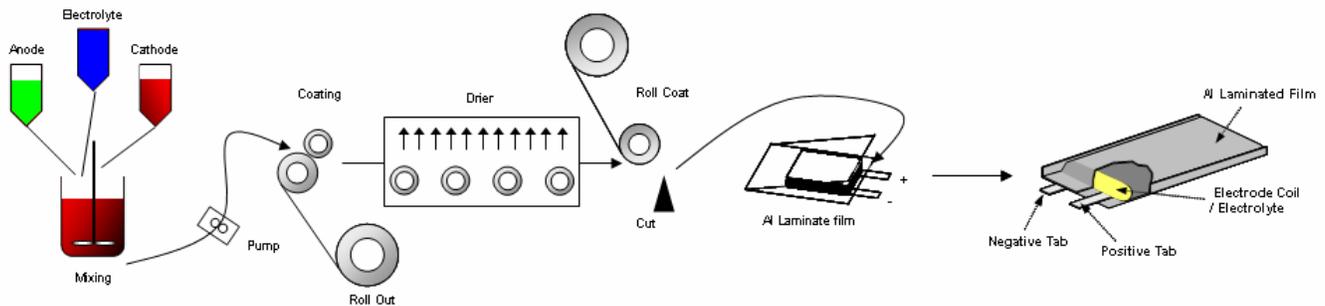
Source: Ric Pulop and Yet-Ming Chiang.

Exhibit 5 Battery Self Organization

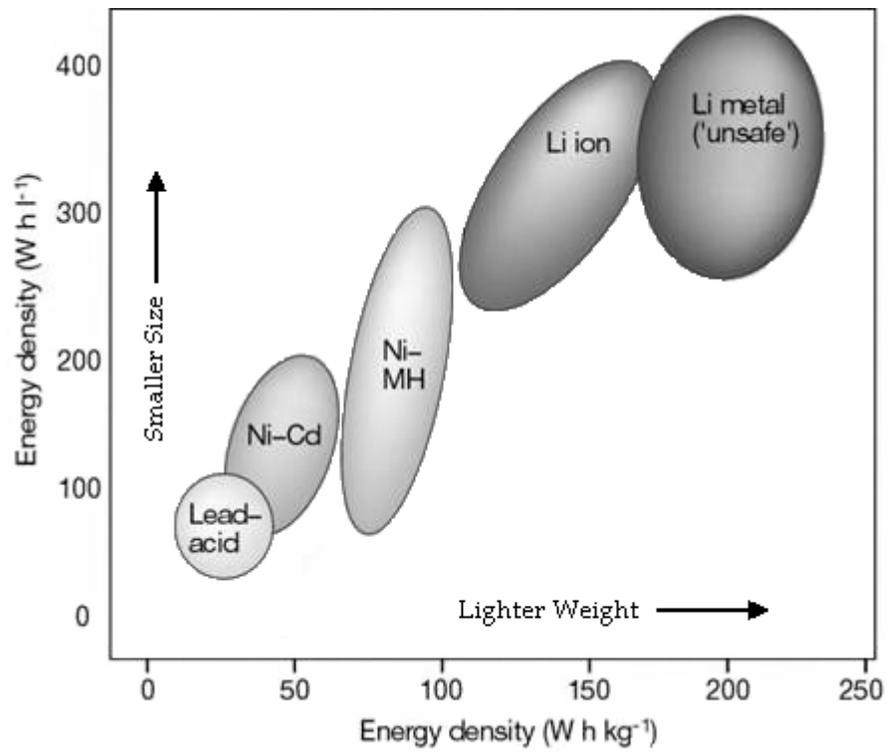


Source: Adapted from Professor Yet-Ming Chiang's notes.

Exhibit 6 A123 Battery Cell Manufacture



Source: Ric Fulop.

Exhibit 7 Sizes and Weights of Materials Commonly Used in Batteries

Source: J.M. Tarascon and M. Armand, *Nature* 414 (2001), p. 359.