



Long-Life, Self-Recharging BetaBattery™

Technology and Market Overview

Introduction

The BetaBattery™ is a long-life, self-recharging micro-power unit. It will be the power source of choice for a variety of defense and medical applications where it is vital that continuous, unattended power be delivered in inaccessible locations for 10-20 years or more.

This Overview summarizes the status of the technology being developed by BetaBatt that underpins its commercialization goals. The market and the competition are also discussed briefly.

The tasks leading to commercialization include producing new high performance 3D diodes using improved processes and materials, and stacking the 3D diodes to make hermetic Charger units containing the tritiated polymer energy source. The final BetaBattery™ assembly consisting of Charger, charge control board and thin-film rechargeable Lithium batteries will be packaged in a certified, hermetically-sealed case.

The completion of this work will allow BetaBatt to produce 100 BetaBattery commercial-ready prototype units per month in order to meet all the testing and qualification needs for the next 2 years. During this time, BetaBatt expects to document the entire suite of production processes and ramp up to build and deliver thousands of BetaBattery power sources to customers annually.

Market research performed by BetaBatt shows that there is an unserved need for micro-power batteries lasting for 20 years or more. The present size of this market is \$200-\$300 million. Trends suggest growth to over \$1 billion a few years after commercial acceptance occurs. There are 2 principal market segments which can be identified at this time. The first segment is applications for instant performance of a vital function at any time within a 20 year period. These applications are primarily in the defense, intelligence, and security arenas where the cost of the power source is a very small fraction of the value of the function performed or the property protected. The second segment is medical implant power where human health or function is maintained or improved. The primary benefit in this case is continuous operation for 10 to 20 years with no need for another surgical intervention.



The BetaBattery™

The BetaBattery™ under commercial prototype development by BetaBatt is a long-life, self-recharging battery made up of 4 primary components:

1. Charger: Tritiated 3D silicon diodes
2. Storage: Thin-film rechargeable Lithium battery
3. Charging Control Board: Microelectronic circuitry to match the Charger to the rechargeable battery
4. Case: NRC-approved hermetically-sealed case for secure containment.

Figure 1 sketches the basic BetaBattery™ fabrication and assembly procedure. Each of the steps illustrated has been subjected to considerable development effort and refinements are continuing.

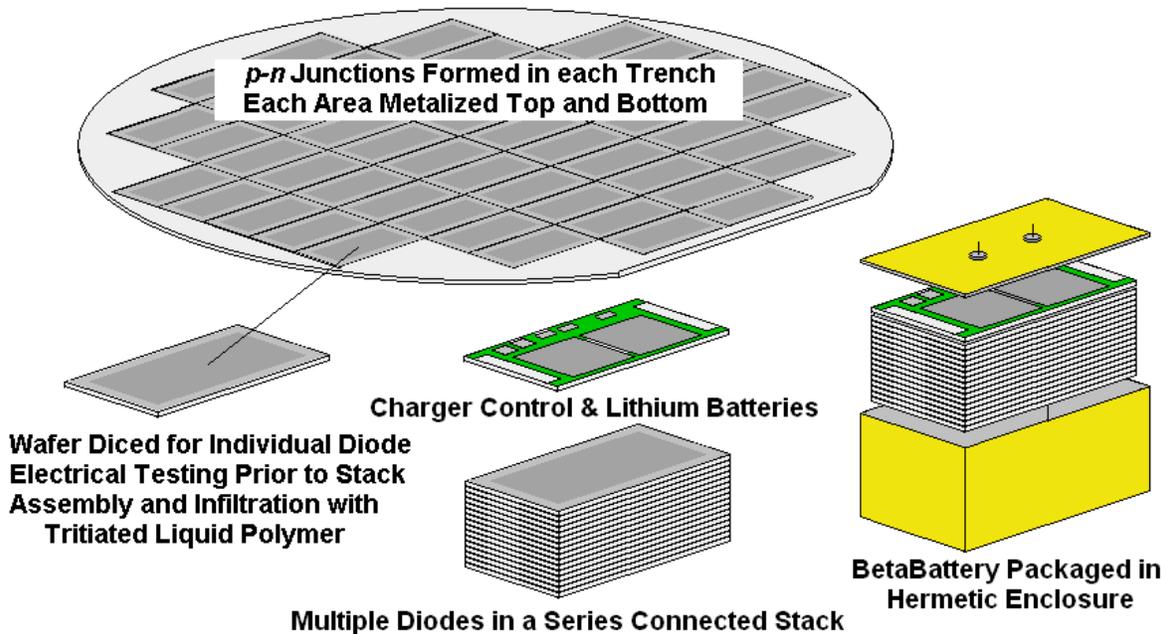


Figure 1. Prototype BetaBattery™ fabrication and assembly steps.

The voltage, current, power, energy, duty cycle, and lifetime characteristics are designed for each specific application. In general, the three key characteristics of the BetaBattery are:

- Long life: 10 to 25 years
- Low power: < 5 volts, <900 μ W
- Small size: coin to standard 9v battery

The long-life, self-recharging feature is the differentiating characteristic of the BetaBattery.

Standard photolithography, dopant diffusion and direct electrode deposition processes are done in a semiconductor fabrication facility to produce the 3D



diodes. The complete 3D diode chip stack is hermetically sealed, excepting the fill tubes, using standard semiconductor soldering techniques. The tritiated butyl rubber (TBR) polymer energy source is infiltrated into the stack at an appropriately-licensed radioactive materials handling facility. In the last step, the fill tubes are permanently sealed. At appropriate points during 3D diode fabrication and assembly, electronic measurements are performed to assure the desired performance levels have been achieved.

The Charger is also where BetaBatt gains its competitive advantage. Size is critical in the target applications. By virtue of its patented 3D geometry, BetaBatt can provide 10 times the energy density and power density of its competitors, who use a planar (2D) construction.

Inherently Safe Design

From the beginning, the BetaBattery was designed to be inherently safe. Tritium only emits low energy electrons which can be stopped by a sheet of paper or a layer of dead skin. The tritiated butyl rubber (TBR) polymer developed by BetaBatt to carry the tritium is biologically inactive and cannot be digested and broken down by normal physiological processes. Thus, once this Tritium energy source is doubly encapsulated, inside the 3D diode stack and then inside the hermetic case, there is no external radiation of any kind. The case itself is mechanically strong enough to resist several atmospheres of overpressure. A 'getter' will be incorporated to absorb any Tritium gas that might be evolved. Finally the helium (³He) resulting from Tritium decay will slowly migrate through the glass-to-metal seals of the electrical feed-throughs.

The Market

This Section summarizes the market research performed by BetaBatt. The initial target markets for BetaBatteries are shown in Table 1. There is constantly increasing interest in fielding Anti-Tamper (AT) units that meet Department of Defense (DOD) requirements. These power sources must supply power for up to 20 years without intervention in order to detect intrusion into classified software and hardware, and destroy the software if necessary. Market acceptance of BetaBattery power sources in this arena will likely take 2-3 years because there are a number of testing and evaluation procedures that must be performed to validate BetaBatteries for use in the DOD complex.

Table 1. BetaBatt Target Markets.

Government and Military	Anti-Tamper and Security, Sensors and Detectors, Health Monitoring of "Smart" Electronics.	10,000-20,000 AT power units annual volume	\$1,500-\$3,000 BetaBattery initial pricing
Medical and Human Health	Pacemakers, Defibrillators, Micro stimulators, Drug delivery.	50,000 pacing power units/year	\$1,500 price per BetaBattery

There is also growing interest in long life betavoltaic power sources for medical implant power. It should be noted that the stringent testing and qualification



regimen necessary for implantable medical devices means that it will be several years before volume delivery can occur in the medical market. BetaBatt has been responding to inquiries and supplying information so that the suitability of BetaBatteries for particular applications can be evaluated.

The Competition

Initial markets addressed by the BetaBattery will be those having a long-life requirement without recharging. The lifetime of low power chemical batteries is at most 10 years and extensions beyond this seem unlikely. The main competition in this market is from other betavoltaic battery providers as described below.

Widetronix: This upstate New York competitor has licensed well developed wideband gap SiC semiconductor technology from Cornell University. The maximum power output with its current planar geometry and form factor is less than 1 μ W, but improved output units are being developed according to its Web site (www.widetronix.com). Widetronix costs are likely similar to or higher than BetaBatt's own estimates. Widetronix appears to be moving forward according to its business plan.

City Labs: This Florida-based, tightly-held competitor is also developing tritium betavoltaic power sources. Its semiconductor diode technology is proprietary, but a wide band gap type is likely (e.g., gallium nitride). City Labs device geometry is planar with stacking to increase power output (www.citylabs.net). Fabrication costs are probably similar to those of Widetronix.

Qynergy: This one-time competitor is based in Albuquerque, but has recently focused its efforts elsewhere according to BetaBatt's contacts. Although their Web site (www.qynergy.com) lists the availability of betavoltaic power devices, they are now developing capacitors and detectors.

BetaBatt's technology has several advantages with respect to its direct competitors. BetaBatt's capability of delivering more current than competitors from pre-prototype BetaBattery units was verified by a large defense contractor. BetaBatt has built-in flexibility to produce a variety of form factors and power delivery options for the market place at relatively little effort and cost.

Typical fabrication techniques used by competitors involve 'simple' exposure to Tritium gas. Migrating to volume fabrication of betavoltaic devices using this technique is fraught with problems. Manual handling of tritiated chips would be necessary. The associated tasks are laborious, time-consuming, wasteful, and prone to contaminating the work area.

BetaBatt has kept manufacturability and commercialization as a key element in its planning from the beginning. Thus documented improvements such as



the 3D trench chip design and the liquid tritiated polymer infiltration, allows for ease of fabrication with near zero waste while safely and effectively containing the radioactive energy source in a doubly-encapsulated hermetic environment.

Progress to Date

The Charger component of the BetaBattery™ is an energy-harvesting device which converts nuclear decay energy into electricity. The principle of operation is the same as that of a solar cell, except that instead of photons from the sun, the energy is provided by electrons (beta particles) emitted by the decay of Tritium, the radioisotope of hydrogen¹. Thus, most of the technology associated with solar cells, particularly the silicon (Si) variety, can be brought to bear to improve the Charger performance. The key difference is that betavoltaic devices must be optimized for high performance at low flux levels, equivalent to dim room light.

A nominal Si solar cell in bright sunlight has a conversion efficiency of about 15%. A properly constructed 3D Si diode illuminated by beta decay of Tritium (similar to dim light) should have a conversion efficiency of about 10%. The initial 3D diodes built with NSF SBIR funds had about 1% conversion efficiency. A pre-commercialization award from the State of Texas Emerging Technology Fund (ETF) allowed 3D diode fabrication at a fabrication facility with extensive solar cell semiconductor expertise. Although the electric power produced by pre-prototype tritiated devices was 20 times the current of competitor prototypes, the 3D diode performance was less than the initial units and was judged to be insufficient for commercial units.

To understand the device performance and guide improved process development, BetaBatt sponsored research in 2009 with Professor Ronald L. Carter of the University of Texas at Arlington. A simulation model was generated that could accurately predict the performance characteristics of 3D diode chips based on the silicon material properties. In addition the relevant device fabrication procedures were simulated and optimized so that the desired *p-n* conversion layer can be formed for our 3D diode devices. Together these models have provided guidance for modifying the 3D chip fabrication processes to achieve the high performance improvements for optimum betavoltaic conversion and obtain 5% efficiency in initial prototype BetaBatteries. BetaBatt now has a thorough understanding of the material and processing parameters needed to build very high performance tritiated 3D Si diode chips.

The other extremely significant accomplishment is the development of a new method to preassemble the 3D diodes into the Charger stack before infiltration with Tritium. The original method was determined to be unsuited for

¹ Solar cells are photovoltaic devices. Similarly, the BetaBattery Charger is a betavoltaic device.



commercial manufacturing. By redesigning the 3D layout of the diodes, the diodes can be stacked and sealed prior to infiltration thus greatly improving speed of assembly, vastly reducing potential radiation exposure to the workers, and improving the overall integrity of the Charger.

Next Steps

Based on the prior production activities and results, and the simulation analysis described above, BetaBatt is ready to move forward to produce commercial-quality prototype 3D diodes. The next steps to become commercial ready are summarized below:

- A. Complete 3D diode design and fabrication effort
- B. Integrate charger stack with associated electronics
- C. Continue NRC regulatory process for BetaBatteries™ and enclosures
- D. Optimize synthesis for tritiation

Each of these steps has been divided into testing, evaluation, and parameter adjustment procedures. Other elements of this work include the complete process documentation necessary to build devices. The testing for certification by the Nuclear Regulatory Commission (NRC) will be completed and any necessary design modifications for the hermetic case will have been implemented. The goal is to have a complete packet for regulatory certification delivered to the NRC for consideration within a year.

Future Product Development

BetaBatt's main competitors use so-called wide band gap semiconductors such as silicon carbide (SiC). Prototype BetaBatteries will produce more than 800× the current relative to competitors' prototype betavoltaic devices. However, SiC offers 4-5× more power output than equivalent silicon devices. Using SiC would allow BetaBatteries to have power densities >1000-1500 $\mu\text{W}/\text{cm}^3$ compared to >250 $\mu\text{W}/\text{cm}^3$ electric power with Si. BetaBatt expects to begin investigation into using a wide band gap semiconductor like SiC as soon as feasible.

BetaBatt believes that it will be able to continue contract manufacturing with a semiconductor fabrication facility for the foreseeable future. However, it is probable that we would have to consider building our own tritiation facility here in Texas instead of using out-of-state service providers.

Conclusion

There is a market for the long-life, self-recharging battery, and BetaBatt has a proprietary competitive advantage to supply a wide variety of products to serve this market. BetaBatt has identified product improvements to reach the required performance levels. BetaBatt is poised to move forward and move to successful commercialization by building BetaBatteries™ that have unique and world class performance.

Appendix

A Ragone Plot illustrates the correlation between energy content (Watt-hours) and rate of energy delivery (Watts), normalized to some basic unit such as mass (usually) or volume². Figure 2 shows a Ragone Plot for Batteries and Betavoltaics that has been developed to illustrate the synergy of combining a betavoltaic Charger with a rechargeable chemical battery as is being done in the BetaBattery™ micro-power source.

The key point is that the energy content of betavoltaic power sources like the BetaBattery is quite high, but the instantaneous power delivery is limited. The reverse is true for chemical batteries and capacitors. Most BetaBattery applications have an associated duty cycle with a quiescent phase of limited activity and a response phase where it is necessary to perform an action. Thus, production BetaBatteries will have a range of power delivery and duty cycle capabilities. This will allow the integral Lithium batteries to be recharged during inactivity so that the desired function can be performed for each specific application.

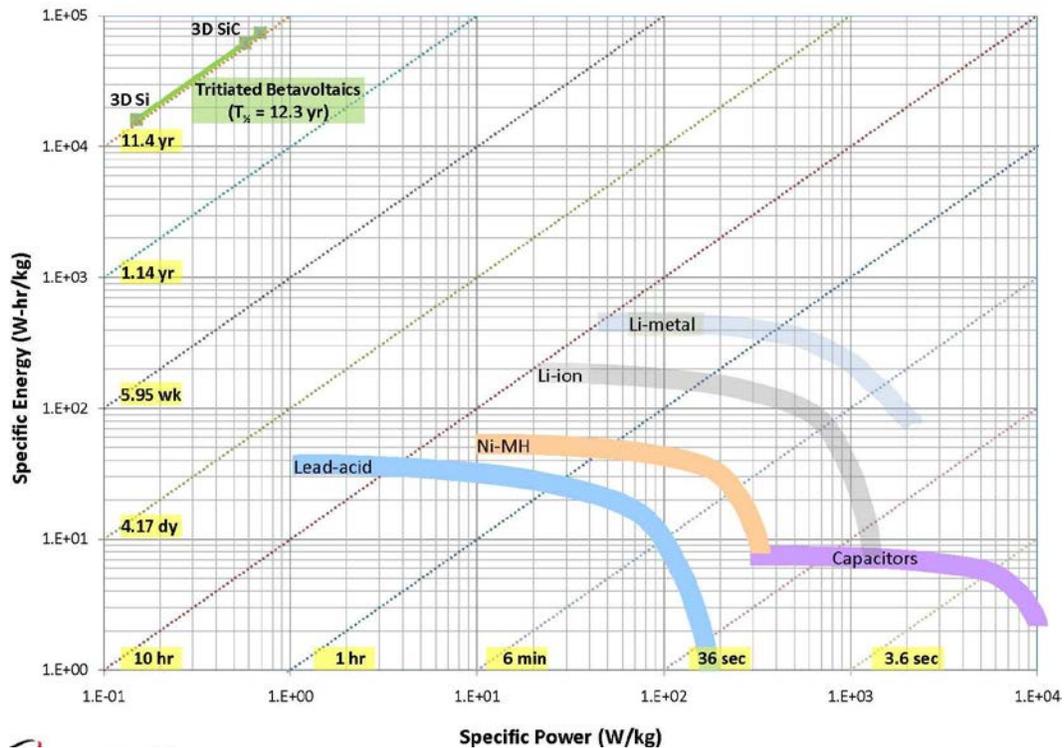


Figure 2. Ragone Plot for Batteries and Betavoltaics. The diagonals labeled with time give an indication of the power delivery period for the technologies shown. (Battery & Capacitor Data: <http://berc.lbl.gov/venkat/Ragone-construction.pps>)

² Recall that 1 Watt = 1 joule per second and 1 Watt-hour = 3600 joules.