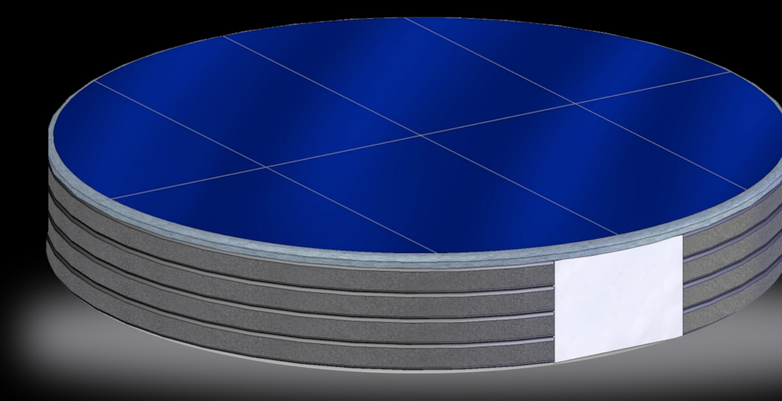
2010

MICRO POWER SOURCE



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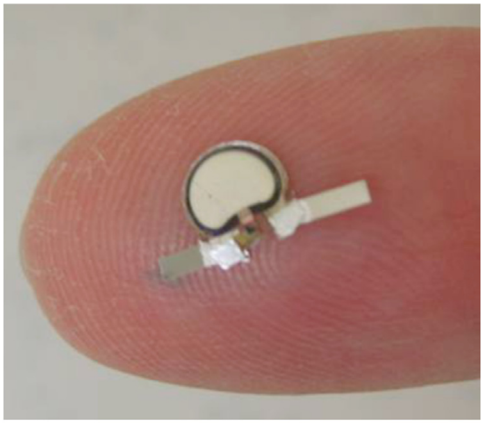

Battery ID: BG81203N12_115B

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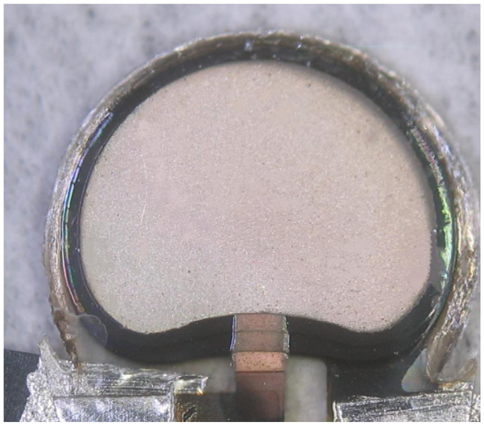

Laser cutout: 5 mm diameter

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Product Name

Micro Power Source

Brief Description

This Micro Power Source is a rechargeable ultra-small form factor that integrates a lithium-ion-based solid electrolyte battery with an ultra-thin photovoltaic collector as an energy harvester.

Product First Marketed or Available for Order

21 February 2009

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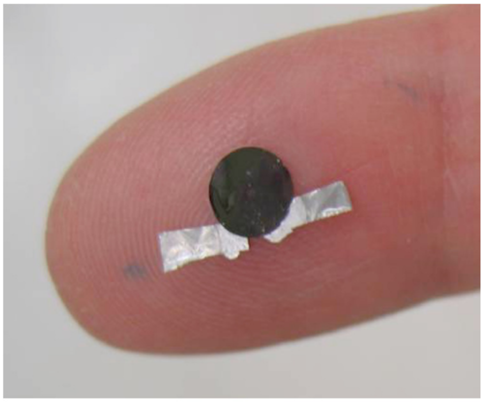
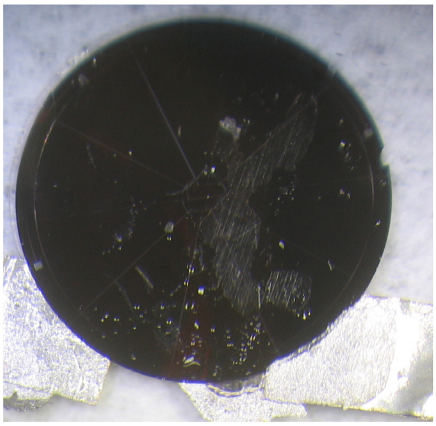


Sample: functional PV/battery integrated device



Laser cutout: 5 mm diameter

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Product Price

The product will be marketed by Front Edge Technology, Inc. with pricing projected to be $10 per unit at high volume.

Patents or Patents Pending

Front Edge Technologies

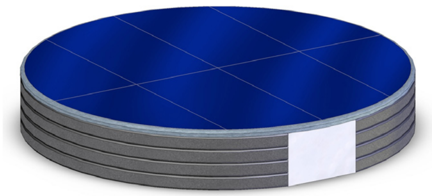
- Victor Krasnov, Simon K. Nieh, and Su-Jen Ting, "Thin film battery and method of manufacture," US patent #6632563 B1, 2003.
- Victor Krasnov, Simon K. Nieh, "Thin film battery and method of manufacture," US patent #7056620 B2, 2006.
- Victor Krasnov, Simon K. Nieh, and Su-Jen Ding, "Method of manufacturing a thin film battery," US patent #6921464 B2, 2005.
- Victor Krasnov, Simon K. Nieh, Fan-Hsiu Chang, and Chun-Ting Lin, "Rechargeable Battery Having Permeable Anode Current Collector," US patent #6713987 B2, 2004.
- Victor Krasnov, Simon K. Nieh, Su-Jen Ting, Paul Tang, Fan-Hsiu Chang, and Chun-Ting Lin, "Sputter deposition of Lithium Phosphorous Oxynitride material," US patent #6863699 B1, 2005.

Pacific Northwest National Laboratory

- Multiple patents on the coating, but PNNL's commercialization partner requests no disclosure of patent numbers.

Sandia National Laboratories

- Technical Advance in preparation.



Photovoltaic Cells

Product's Primary Function

Our product is an ultra-small form factor, energy-harvesting (self-charging) power source encapsulated in a polymer coating. It functions by integrating a lithium-ion based solid-state battery with a thin photovoltaic (PV) collector. The battery is a solid-state system that employs a lithium phosphorus oxynitride (LiPON) solid-state electrolyte. It is charged by an energy-harvesting PV device that is 10-µm thick, single-junction, 10-cell, and silicon (Si)-based. The entire system is environmentally sealed using a specially developed polymer coating. The volume of the system is approximately 1 µL (5 mm in diameter and approximately 50 µm thick). it has an energy density greater than 300 watt-hours per liter (Wh/L), which is significantly higher than nickel-metal hydride (Ni-MH) systems (~175 Wh/L)[1] and is comparable to traditional lithium-ion (Li-ion) systems (~250-360 Wh/L)[2]. The battery can easily handle 3,500 charge/discharge cycles. Taking this durability into account, the apparent energy density of the system is over 10,000 Wh/L, significantly more than any available single-use technology (i.e., nonrechargeable batteries, fossil fuels, etc.).

We originally designed and built the product as part of a Defense Advanced Research Projects Agency (DARPA) program, but commercial applications have been evident from the start. The most likely commercial applications include (1) self-powered smart cards, which would enable enhanced user features and security; (2) self-powered environmental sensors (e.g., strain, crack, and pressure sensors to improve the efficiency and reliability of large wind turbines); and (3) self-powered tags for material tracking. We can easily change the form factor and the energy harvester of the Micro Power Source to open up many other application spaces.

"Successful development of the Micro Power Source required integrating and advancing five new technologies."

[1] *http://www.duracell.com/oem/Pdf/others/TECHBULL.pdf*

[2] *http://en.wikipedia.org/wiki/Lithium-ion_battery*

Our product combines three new component technologies and two advanced manufacturing techniques:

- Front Edge Technology's thin-film rechargeable lithium cells
- Sandia National Laboratories' ultra-thin photovoltaic cells
- Pacific Northwest National Laboratory's ultra-thin sealing material
- Front Edge Technology's precision masking technique for manufacturing micro thin-film batteries
- The UCLA Nanofabrication Lab's assembly and packaging techniques.

Back side of a 5 mm diameter, 5 µm thick PV cell after shadow mask metallization. The shape of the pads corresponds to the polarity of the PV cell.

Although some of these technologies have been demonstrated separately, in our product they are integrated together for the first time and, in fact, each technology has been advanced during the development of this system.

Product's Competitors

Several companies offer small-volume power sources, but none integrates power, storage, and renewable energy recharging into a single package like the Micro Power Source. No commercial system captures all the attributes of the Micro Power Source.

Comparison Matrix

Power Source Type	Organization	Volume (mm^3)	Energy Density (Wh/L)	Power Density (W/L)	Cycle Life	Service Life (yrs)
Micro Power Source	Front Edge Technology	1	15000 (50 cycles) 300 (single cycle)	1400 (peak)	3500	10
Solid-State Thin Film Battery	Front Edge Technology	6	160	1500	3000	10
Li-ion Battery	Quallion	86	126	400	1000	5
Solid Fuel Cell (Zn-Air)	Rayovac	57	820	80	none	N/A
Radioactive Material	BetaBatt	775	5900	0.00004	N/A	12
Micromachined Heat Engine	MIT	339	1366	12000	N/A	N/A
Micromachined Fuel Cell	UCLA	170	5	17	N/A	N/A
Micromachined Ni-Zn Battery	BYU	10	120	7500	1000	N/A
Microfabricated Battery on Si	JPL	0.05	3.9	20	1000	N/A

How Product Improves on Competition

The combination of ultra-low system volume and a spectacularly high energy density set this product apart from its competitors. Construction of the battery and the PV are based on existing manufacturing technologies that are amenable to volume manufacturing scale-up. With volume manufacturing, the cost per unit will be very competitive with existing systems. The safety and reliability of the battery are enhanced by the elimination of liquid electrolyte. The inclusion of the energy harvester increases the apparent energy density to levels that are orders of magnitude higher than the competition.

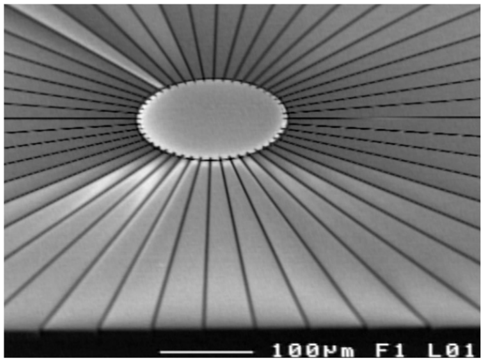
Product's Prinicpal Applications

Sandia National Laboratories partnered with Front Edge Technologies and Pacific Northwest National Laboratory to develop the Micro Power Source as part of a program sponsored by DARPA, but DARPA has not revealed the applications for which it wants to use this advanced technology. In the commercial realm, the Micro Power Source has the potential to revolutionize several industries, including hand-held electronics, cyber security, and alternative energy.

Many potential commercial applications exist for the Micro Power Source. They include the following:

- self-powered smart cards, which would enable enhanced user features and security
- self-powered environmental sensors (e.g., strain, crack, and pressure sensors to improve the efficiency and reliability of large wind turbines)
- self-powered tags for material tracking (e.g., identification tags with extended range and storage signal that would enable instant inventory of a warehouse)
- ultra-compact and ultra-lightweight continuous medical monitors
- low-cost sensorization of legacy equipment
- a power source for micro satellites.

We can easily change the form factor and the energy harvester of the Micro Power Source to discover many other application spaces. Batteries are usually the largest item in today's electronic devices (mobile Phone:s, music players, etc.). Many consumers consider size and weight as critical factors when making purchase decisions. By replacing a bulky and heavy liquid-electrolyte battery with a super thin solid-state battery and an energy harvester (whether PV, vibrational, or radiofrequency), portable electronic devices can be made much smaller, thinner, and lighter.



Perspective scanning electron microscope image of the front side of a 5 µm thick PV cell.

Other Applications

This versatile Micro Power Source can be used for many applications that require a power source with very small form factor and high power density—e.g., active smart cards; self-powered radio-frequency identification tags; self-powered portable memory devices; in-situ power for industrial process monitors; and remote, untethered sensors and transmitters.

Summary

Any product that advances the state of the art for small form factor, self-charging, wireless power sources has the potential to affect millions of people by enabling new technologies or by improving existing technologies by making them more efficient, less expensive, and more environmentally friendly. Our Micro Power Source has that potential.

Successful development of the Micro Power Source required integrating and advancing five new technologies. In the process, we were able to display the power of today's advanced engineering techniques.

The Micro Power Source provides more than 10,000 Wh/L of energy density at a volume of 1 µL. To give some perspective on the scale of this achievement, consider that one AA alkaline battery has an energy density of about 450 Wh/L and a dime has a volume of about 340 µL. To our knowledge, there are no comparable energy harvesting, self-charging power sources available anywhere today.

Our Micro Power Source represents a significant technical advance, one that will impact the future of micro-devices by enabling them—through their energy-harvesting capacity—to become active, rather than passive, participants in their environments. This technology will certainly impact micro-device industry and is thus worthy of consideration for a 2010 R&D 100 Award.

"Imagine being able to inventory an entire warehouse with the push of a single button."

Power Source	Power Density	Volume
Micro Power Source	10,000 Wh/L	1 µL
AA Alkaline Battery	450 Wh/L	340 µL

Power source comparison

Affirmation

By uploading this form to R&D Magazine's website you affirm that all information submitted as a part of, or supplemental to, this entry is a fair and accurate representation of this product.

Todd M. Bauer

Todd Bauer

Appendicies

Appendix A: Articles

- *High-voltage Series Connected Si Photovoltaic Cells*
- *High Voltage with Si Series Photovoltaics*

Appendix B: DARPA BAA

- *BAA 06-33 Proposer Information Pamphlet*
- *Micro-Power Source Proposal: Volume I Technical and Management Proposal*

High voltage series connected Si photovoltaic cells

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ABSTRACT

This report describes the features of monolithic, series connected silicon (Si) photovoltaic (PV) cells which have been developed for applications requiring higher voltages than obtained with conventional single junction solar cells. These devices are intended to play a significant role in micro / mini firing systems and fuzing systems for DOE and DOD applications. They are also appropriate for other applications (such as micro-electro-mechanical-systems (MEMS) actuation as demonstrated by Bellew et. al.) where electric power is required in remote regions and electrical connection to the region is unavailable or deemed detrimental for whatever reason. Our monolithic device consists of a large number of small PV cells, combined in series and fabricated using standard CMOS processing on silicon-on-insulator (SOI) wafers with 0.4 to 3 micron thick buried oxide (BOX) and top Si thickness of 5 and 10 microns. Individual cell isolation is achieved using the BOX layer of the SOI wafer on the bottom. Isolation along the sides is produced by trenching the top Si and subsequently filling the trench by deposition of dielectric films such as oxide, silicon nitride, or oxynitride. Multiple electrically isolated PV cells are connected in series to produce voltages ranging from approximately 0.5 volts for a single cell to several thousands of volts for strings of thousands of cells.

Keywords: High voltage, monolithic, series connection, photovoltaic cell, SOI, trench isolation, solar cell, open-circuit voltage

1. INTRODUCTION & BACKGROUND

Micro / mini firing systems and fuzing systems for Department of Energy (DOE) and Department of Defense (DOD) applications require compact voltage conversion systems. Such systems are also required for applications, such as MEMS, where electrically isolated regions require power without electrical connection to those regions. Series connected PV cell arrays, illuminated by an optical source, are being developed to address this requirement. The advantage inherent in using series connection of multi-junction converters is that higher voltages are generated than the output voltage directly produced by single-junction PV converters. To boost the voltage obtained from single-junction PV converters to useful values, a transformer or DC-to-DC converter is required. This approach results in substantial loss in the overall system conversion efficiency and adds to the weight and volume of the system.

A PV converter is a semiconductor p/n junction fabricated in such a way that minority carriers generated by the absorption of light are collected mostly by diffusion process. An electric field at the metallurgical junction supplies energy to these carriers, providing a photovoltage to drive a load.

The key factor that describes the number of electron-hole pairs generated per incident photon per depth (i.e. quantum efficiency) is the absorption coefficient of the semiconductor material. Figure 1 shows the absorption of light in semiconductors that are commonly used for optoelectronic applications. The semiconductor band-gap energies (E_g) are also included. The absorption coefficient (α) drops off sharply at the wavelength ($\lambda = 1.24/E_g$) where the photon energy is equal to the band-gap energy. Negligible absorption occurs for photons with energy smaller than the material's E_g. At short wavelengths, the absorption coefficient is large and the majority of the photons are converted into electron-hole pairs near the surface of the semiconductor. A small absorption coefficient at longer wavelengths, on the other hand, allows deep penetration of photons so that the 'base' of the solar cell becomes more important in carrier collection. Furthermore, a semiconductor can collect photons with the energy of the band-gap with good efficiency. Photons of lower energy are not absorbed and those with high energy are reduced to E_g by thermalization. Therefore, the curve of efficiency versus band gap goes through a maximum (Figure 2). It can be observed that Si is not at the maximum but relatively close to it. A much more serious point is that Si is an indirect semiconductor and, therefore, light absorption is

Optical Technologies for Arming, Safing, Fuzing, and Firing, edited by William J. Thomes, Fred M. Dickey,
Proc. of SPIE Vol. 5871, 58710F, (2005) · 0277-786X/05/$15 · doi: 10.1117/12.619527

High Voltage with Si Series Photovoltaics

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Abstract

A monolithic crystalline Si photovoltaic device, developing a potential of 2,120 Volts, has been demonstrated[12]. The monolithic device consists of 3600 small photovoltaic cells connected in series and fabricated using standard CMOS processing on SOI wafers. The SOI wafers with trenches etched to the buried oxide (BOX) depth are used for cell isolation.

The photovoltaic cell is a Si pn junction device with the n surface region forming the front surface diffused region upon which light impinges. Contact is formed to the deeper diffused region at the cell edge. The p+ deep-diffused region forms the contact to the p-type base region. Base regions were 5 or 10 µm thick.

Series connection of individual cells is accomplished using standard CMOS interconnects. This allows for the voltage to range from approximately 0.5 Volts for a single cell to above a thousand volts for strings of thousands of cells. The current is determined by cell area. The voltage is limited by dielectric breakdown. Each cell is isolated from the adjacent cells through dielectric-filled trench isolation, the substrate through the SOI buried oxide, and the metal wiring by the deposited pre-metal dielectric. If any of these dielectrics fail (whether due to high electric fields or inherent defects), the photovoltaic device will not produce the desired potential. We have used ultra-thick buried oxide SOI and several novel processes, including an oxynitride trench fill process, to avoid dielectric breakdown.

Introduction

Several applications could benefit from a small form factor, high voltage photovoltaic device that can produce 0.5 Volts to over 2000 Volts. These applications include MEMS actuation, which requires approximately 1 to 100 Volts; on-chip microelectronic voltage supply (2 to 30 Volts); and fuzing (greater than 1,500 V). The goals of the program were to develop CMOS-compatible monolithic series connected PV cells with a total area of less than 20 mm^2 that met the Voltage requirements of various applications. CMOS compatibility means that the devices are not only made using standard CMOS processing techniques, but that CMOS can be built on the same wafer and at the same time that the PV cells are built. CMOS compatibility was a requirement for two reasons: first, reduced process complexity and costs; and second, some applications would benefit from a one-chip form factor.

Device construction

Figure 1 shows both a cartoon and SEM cross-section of a series connected PV. 150 mm SOI wafers were used for the fabrication of the PV cells[345678910]. The thickness of the buried oxides (BOX) of the different wafers used was between 2 and 3 µm. The thickness of the top-Si was between 5 µm and 10 µm. All top-Si was p-doped. SOI was chosen as a method of isolating the bottoms of each discrete PV cell; and wide trench isolation is used to isolate the sides of each cell. The trench isolation is formed by dry reactive ion etching through the entire

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Optical Technologies for Arming, Safing, Fuzing, and Firing II, edited by William J. Thomes, Jr., Fred M. Dickey, Proc. of SPIE Vol. 6287, 62870D, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.683769

Dear **BAA 06-33** Proposer Information Requester:

The BAA 06-33 Proposer Information Pamphlet is enclosed in response to your request. This pamphlet is divided into three sections.

SECTION I: Proposer Information provides further information on Micro-Power Sources (MPS), the submission, evaluation, and funding processes, proposal formats, and other general information.

SECTION II: Broad Agency Announcement (BAA) 06-33 Micro-Power Sources (MPS) is a reprint of the BAA which was posted on the Federal Business Opportunities (FedBizOpps) website at http://www.fedbizopps.gov/ and Grants.Gov (Grants.Gov) website at http://www.grants.gov/.

SECTION III: Defense Advanced Research Projects Agency/ Microsystems Technology Office (DARPA/MTO) provides information on current programs within MTO.

Thank you for your interest in BAA 06-33 Micro-Power Sources (MPS).

Sincerely,

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Micro-Power Source Proposal

Volume I

Technical and Management Proposal

Section I. A. Administrative

A. Cover Sheet

(1) BAA Number:	BAA 06-33
(2) Technical area:	Micro-Power Sources
(3) Lead organization submitting proposal:	Front Edge Technology, Inc. 13455 Brooks Drive, Suite A, Baldwin Park, CA 91706 Firm's Taxpayer ID: 95-4494586 CAGE Code: 3AXZ4 DUNS #: 877927699
(4) Type of business:	Small Disadvantaged Business
(5) Contractor's reference number	DAP681
(6) Other tem members / type of business:	(a) Sandia National Laboratory Type of business: Other Nonprofit (b) Battelle/Pacific Northwest Division Type of business: Other Nonprofit (c) University of California at Los Angeles Type of business: Other Educational (d) Dr. Jay F. Whitacre Type of business: Consultant, Individual
(7) Proposal Title:	Micro-Power Source
(8) Technical point of contact:	Dr. Simon K. Nieh 13455 Brooks Drive, Suite A Baldwin Park, CA 91706 Tel: (626) 856-8979, Fax: (626) 851-1369 email: simonnieh@frontedgetechnology.com
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National Nuclear Security Administration