WHITE PAPER

Organic-Free, All-Solid-State Thin-Film Batteries for Cell Phones, Tablets, and Future Devices

Energy Densities Greater than 700Wh/liter

Manufactured for Less than $1/Wh

Fully Packaged as Thin as 110µm

Inherently Safe, Cannot Burn

Technical White Paper – May 2012

For more information on this and other IPS products, please visit the IPS web site, or contact us by email or phone.
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Organic-Free, All-Solid-State, Thin-Film Batteries for Cell Phones, Tablets, and Future Devices

Overview

Ultra-thin cell phone and tablet size batteries can now be manufactured economically (<$1/Wh) by Physical Vapor Deposition (PVD)-based thin-film battery technology. These all-solid-state, thin-film batteries offer very desirable properties, such as their unrivaled thinness (starting at 0.1mm), inherent safety (cannot burn or explode) and unprecedented energy densities of more than 700Wh/liter (fully packaged). This white paper presents how these solid-state, thin-film batteries will displace lithium-ion prismatic batteries in consumer electronic products.

Introduction

Infinite Power Solutions, Inc. (IPS) is the global leader in developing and manufacturing solid-state rechargeable thin-film batteries, which are used in a variety of wireless sensor and backup power applications. IPS has invested heavily into R&D and continues to develop solid-state battery solutions that go well beyond the energy storage capacity and energy density of its current products, or even that of existing lithium-ion technology. This paper illustrates how IPS has pushed the limits of its existing thin-film battery process with the ability to manufacture “high capacity” thin-film cells. This sets the stage to then stack such high capacity cells to form an all-solid-state, thin-film battery pack with unrivaled thinness, energy density and safety to power next generation cell phones and tablets.

The combination of size, performance and safety advantages of IPS’ all-solid-state technology is “game changing” in that it benefits visionary OEMs who wish to experience the market share gains, pricing power and greater profits in the fast growing smart phone and tablet markets. Because today’s consumer electronics are increasingly commoditized on the hardware side, it is more important than ever for OEMs to seek competitive advantages. The form factor and performance benefits of this all-solid-state battery technology allow for the OEM to leverage a defendable, sustainable and significant advantage in the hardware areas of style and performance, which are arguably the most important characteristics to consumers.

Consumers will benefit by experiencing thinner mobile products that have longer run times and improved safety. It has already been demonstrated in the smart phone and tablet markets that a substantial amount of the consumer market is willing to pay a noticeable premium for superior styling combined with strong performance.

Inherently Safe

It cannot be stressed enough that IPS’ organic-free, all-solid-state, thin-film batteries, with their inorganic, non-combustible and non-reactive electrolytes (e.g., LiPON) are inherently safe and cannot suffer from thermal runaway. It is simply not possible for such cells to burn or explode, regardless of use or abusive conditions. In contrast, lithium-ion prismatic batteries, with their liquid organic electrolyte components, are prone to thermal runaway and can fuel internal battery chemical reactions that may have been triggered by abusive conditions such as electrochemical (e.g., overcharge or short-circuiting), thermal (e.g., temperatures inside a hot car) and/or mechanical (e.g., puncturing).

Environmental concerns are also improved because solid-state batteries have no heavy metals and contain no toxic chemicals. They make the products they power last longer so they are less likely to be discarded prematurely. They are even manufactured in such a way that there are no undesirable by-products or chemicals discharged into the air or water during their “clean-tech” style fabrication.

Detailed Description of an All-Solid-State, Thin-Film Battery

IPS has successfully fabricated 2" x 1" (50.8mm x 25.4mm) proto-type high capacity solid-state, thin-film cells that have been delivered to customers in their fully packaged state. These proto-type cells supplied 1.25mAh/cm^2 on single-sided, coated metal foil substrate using some of IPS' granted patents (U.S. Pat. Nos. 8,021,778 and 7,959,769).

Fabricating these thin-film cells in double-sided mode using another IPS granted patent (U.S. Pat. No. 7,993,773) allows the fabrication of 2.5mAh of capacity per 1cm^2 of substrate foil. These double-sided, solid-state, thin-film batteries can be fabricated with a thickness of 104µm in the unpackaged, charged state wherein the cathode and anode are fully expanded. A cross-sectional sketch displaying the details of such a double-sided cell is shown in **Figure 1**.

The thinnest incarnation of these double-sided, solid-state, thin-film batteries can be packaged by employing IPS' 3µm thin-film encapsulation at the outside of each cell (U.S. Pat. Application No. 2009/0181303). This thinnest design achieves 10mWh (2.5mAh * 4V) per square-centimeter of footprint at about 110µm of fully packaged thickness. Depending on the actual footprint size of the double-sided, solid-state, thin-film battery, between 80-95% of this footprint can be fabricated as active electrochemical area (determined by the area of the positive cathode) thereby still achieving energy densities in the range of 730-860 Wh/liter. These ultra-thin batteries will enable future products of unprecedented thinness.

IPS currently employs a metal film encapsulation for the outer packaging (U.S. Pat. Application No. 2007/0202395), which is illustrated in **Figure 2**. IPS has already developed viable stacking architectures for multiple, un-packaged, double-sided, solid-state, thin-film batteries into an all-encompassing battery encapsulation (**Figure 3**). These batteries achieve more than 700Wh/liter in their fully packaged state. More details of such batteries are presented in the next section.

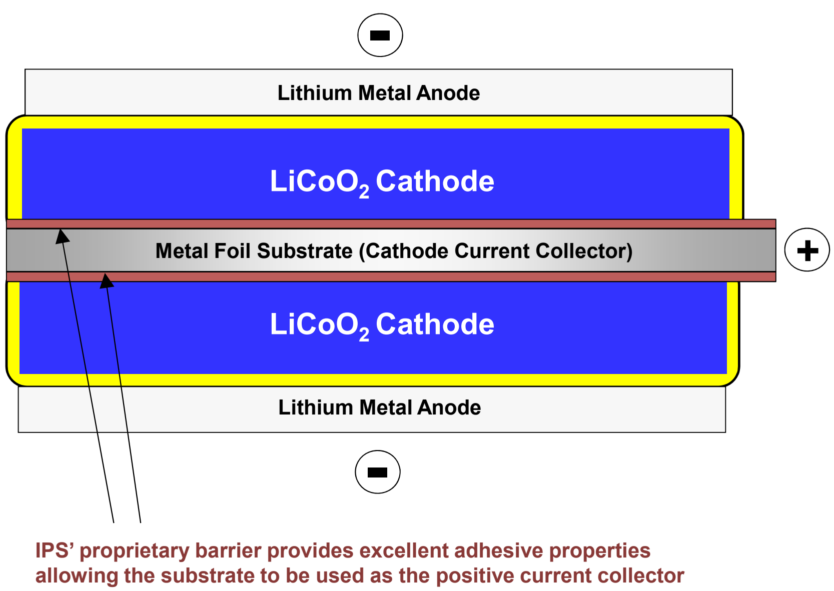

Figure 1 – Cross-sectional sketch of an IPS double-sided, solid-state, thin-film battery (unpackaged) that in the fully charged state is 104µm thick and provides 2.5mAh/cm2 at 4V. The yellow layer represents the thin-film electrolyte layer.

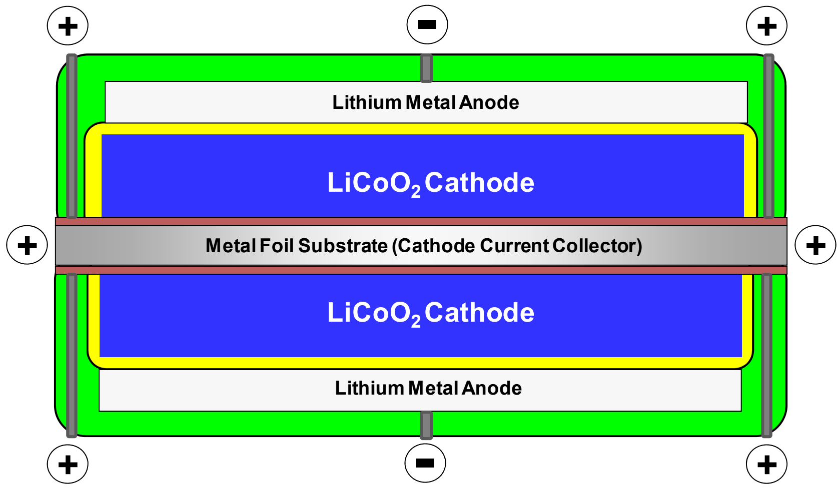

Figure 2 – Cross-sectional sketch of an IPS double-sided, solid-state, thin-film battery packaged with IPS' metal film encapsulation (green areas with positive and negative terminal feedthroughs).

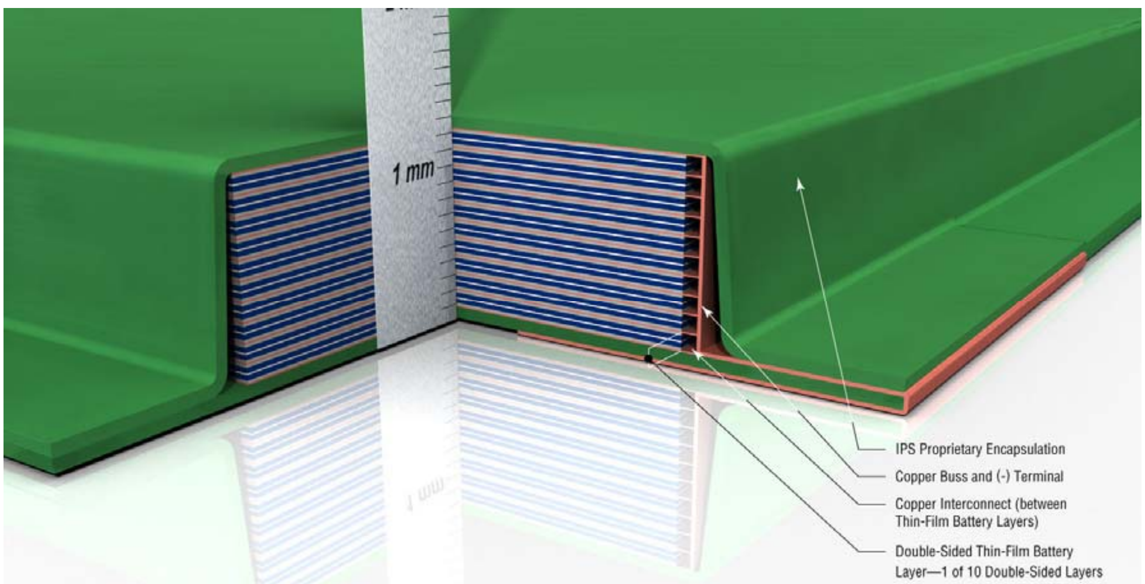

Figure 3 – Cut-away sectional view of an IPS solid-state, thin-film battery packaged with IPS' metal film encapsulation (green). The shown battery could be a 1.4Ah cell phone battery of 1.3mm thickness (three times thinner than prismatic lithium-ion batteries) comprising ten double-sided, unpackaged, solid-state, thin-film batteries (104µm each) as shown in **Figure 1**. These ten 104µm thin batteries are then stacked with eleven interleaving 10µm thin copper foils that serve as the anode current collectors and create a negative feedthrough terminal through IPS' proprietary metal film encapsulation. The termination of the positive terminal is shown in **Figure 4**.

Calculated Performance

IPS thin-film battery packs can be fabricated in much thinner form factors than their lithium-ion prismatic counterparts. **Table 1** presents selected packs whose form factors are much thinner but larger in footprint than their conventional lithium-ion packs of comparable capacity. Graphics illustrating the cross-section of a solid-state, thin-film battery (fully packaged) composed of a 10-stack of double-sided cells are shown in **Figure 3** and **Figure 4.** The underside of this fully packaged battery is shown on the cover page highlighting the positive and negative terminal pads.

Table 1 – Calculated performance characteristics and dimensions of both a cell phone and a tablet type battery completely fabricated using solid-state, thin-film battery technology

Fully Packaged, All-Solid-State, Thin-Film Battery		
	Cell Phone Type	**Tablet Type**
Footprint	110 mm x 53 mm	230 mm x 174 mm
Thickness	1.3 mm	1.5 mm
Voltage	4.2 – 2.8V	4.2 – 2.8V
Energy Density	700 Wh/liter	730 Wh/liter
Capacity	1.4 Ah	11 Ah
Energy (@ 3.95V)	5.4 Wh	44 Wh
Peak Current Capability	7 A	60 A
Cycle-ability	1,000 (to 80% capacity)	1,000 (to 80% capacity)
Leakage	1.2% capacity per year	1.2% per year
Internal Resistance	0.1 Ohm	0.01 Ohm

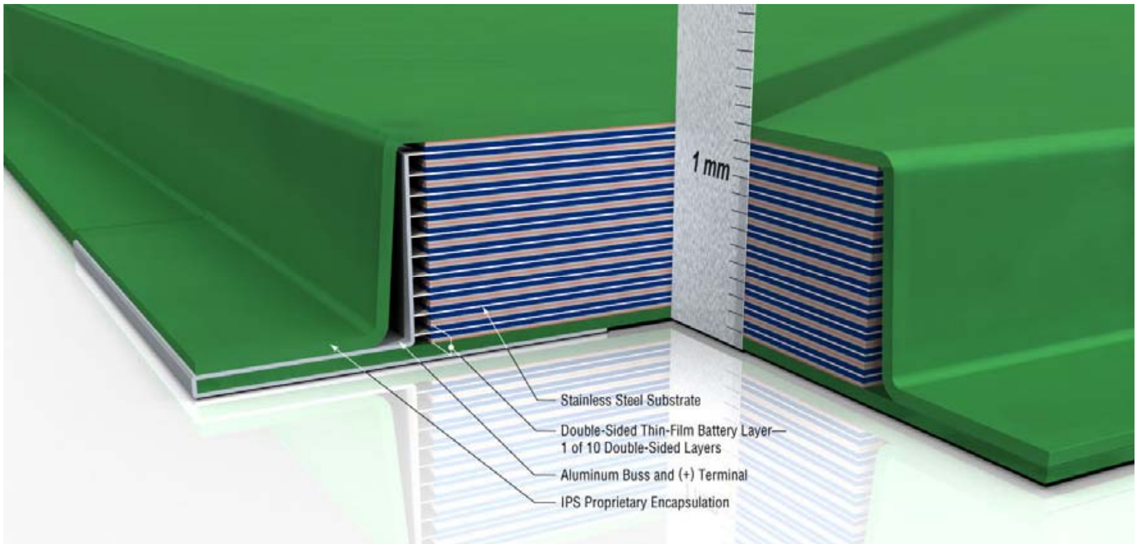

Figure 4 – Cut-away sectional view of an IPS solid-state, thin-film battery packaged with IPS' metal film encapsulation (green). This drawing highlights the positive connections of the fully packaged battery shown in **Figure 3**. These positive connections are made by using the slightly extended substrate foils of the stack of ten double-sided, solid-state, thin-film batteries (104µm thin each) and by then connecting the substrate edges with a vertical metallic foil connector, which then is run through the IPS metal film encapsulation to the underside (or backside) of the fully packaged battery.

Manufacturing Costs

The manufacturing cost analysis of the solid-state, thin-film battery vs. the lithium-ion prismatic battery in **Table 2** makes the following underlying assumptions:

- The solid-state, thin-film battery requires comparable complexity of over/under voltage circuitry as lithium-ion prismatic batteries
- High-volume factories would be based in similar geographic locations as lithium-ion prismatic battery factories
- Equipment (PVD, laser, and RTP) is based on existing in-line, roll-to-roll compartments or related configurations of the flexible display industry
- All assumed deposition rates have been demonstrated at IPS
- IPS' proprietary metal film encapsulation encases a stack of multiple (e.g., 10) double-sided, solid-state, thin-film batteries, each providing 2.5mAh/cm^2 at 4V while being only 104µm thin
- Known cost breakdown of standard lithium-ion prismatic battery is 70% materials, 6% depreciation and 24% everything else (operational costs)

Table 2 – Cost comparison between a standard lithium-ion prismatic cell phone battery and a solid-state, thin-film battery of similar energy

Infinite Power Solutions' Cost Study Analysis		
	Lithium-Ion Factory	**Thin-Film Factory**
Battery Type	Lithium-Ion Prismatic	IPS Thin-Film
Capacity	1420mAh	1360mAh
Operating Voltage	3.6V	3.95V
Total Wh per Unit	5.1	**5.4**
Battery Cost	$4.10	**$4.34**
CapEx	$200,000,000	$440,000,000
Annual Yielded Factory Capacity	96,000,000	30,000,000
Depreciation Scheme	10 years	10 years
Annual Depreciation	$20,000,000	$44,000,000
Depreciation per Unit	$0.21	$1.47
Material Costs per Unit	$2.87	$1.99
Operating Cost per Unit	$1.02	$0.88
Costs per Watt-Hour		
Material	$0.56	$0.37
Depreciation	$0.04	$0.27
Operating	$0.20	$0.16
Total Battery Cost / Wh	**$0.80**	**$0.80**

Note: Details of an exemplary solid-state, thin-film battery can be found in **Table 1**

The capital expenditures (CapEx) assumptions for the lithium-ion prismatic battery are considered typical for factories located in Asia when producing close to 100 million of such batteries annually. A typical cost breakdown for one unit of lithium-ion prismatic battery is detailed above for materials (70%), depreciation (6%) and everything else (24% operating costs). As a result, the three main cost contributions of one 5.1Wh lithium-ion prismatic battery were subsequently normalized to 1Wh of energy, as shown in **Table 2**.

The associated costs of a factory were based on an annual yielded throughput of 30 million fully packaged, solid-state, thin-film batteries of cell phone type size (~1400mAh). Since IPS' solid-state, thin-film batteries are fabricated on a thin metal foil substrate (e.g., 10µm stainless steel), they are preferably manufactured on roll-to-roll equipment with a web that may even be double-sided coated, as patented by IPS (U.S. Pat. No. 7,993,773).

Processing and Manufacturing Equipment

IPS' proprietary manufacturing process consists of only seven processing steps:

1. Sputter deposition of the IPS proprietary barrier layer on the metal foil substrate
2. Sputter deposition and crystallization anneal of the positive cathode layer (e.g., $LiCoO_2$)
3. Patterning of the positive cathode (e.g., by laser ablation)
4. Sputter deposition of the thin-film electrolyte layer
5. Resistive evaporation of the negative metallic lithium anode layer
6. Device singulation and stacking/packaging
7. Battery testing

This simple process leverages flexible panel display, roll-to-roll, large-scale manufacturing equipment along with process and metrology techniques that are readily available and mature with fully established parts, supply chain and support.

The raw material comparison between a lithium-ion prismatic battery and a solid-state, thin-film battery of comparable capacity or energy reveals a few interesting results (see **Table 3**). First, the raw materials (sputter targets and lithium evaporation material, among others) of the solid-state, thin-film battery are less expensive than the lithium-ion prismatic battery materials, mostly due to the expensive organic liquid electrolyte used in the latter. Second, the raw materials are heavily overshadowed by the cost for the over/under voltage control circuit and the outer packaging with which both batteries (lithium-ion prismatic and thin-film) are equipped.

Table 3 – Raw material cost comparison of lithium-ion prismatic vs. solid-state, thin-film cell phone battery

	1420mAh (5.1Wh) Lithium-Ion Prismatic Battery		1360mAh (5.4Wh) Thin-Film Battery			
Raw Materials	**Raw Material Costs Li-Ion**	**Li-Ion Costs**	**Raw Material Costs Thin-Film**	**Target Utilization**	**Deposition Utilization**	**Thin-Film Battery Costs**
LiCoO2 Cathode	$32/kg	$0.32	$38/kg	90%	80%	$0.51
Anode	$20/kg	$0.13	$50/kg	90%	80%	$0.02
Separator / Barrier	$120/kg	$0.11	$10/kg	90%	80%	$0.01
Electrolyte	$50/kg	$0.37	$40/kg	90%	80%	$0.04
Encapsulation		$0.001	$10/kg	90%	80%	$0.02
Substrate		$0.028	$12/kg			$0.08
Auxiliary Materials (Binders)		$0.050				
Raw Material Sub-total		$1.009				$0.69
Cost per Wh of Raw Materials		$0.20				$0.13
Protection Circuitry		$0.90	$0.90			$0.90
Outer Packaging/ Leads		$0.96	$0.40			$0.40
Total Material Cost		**$2.87**				**$1.99**

Based on IPS demonstrated deposition rates and proprietary processes, the total CapEx is approximately $320M plus additional facility costs ($20M), automation ($3M), IT ($5M), battery testers ($20M), printing and packaging ($15M), factory infrastructure ($50M), spare parts ($3M), and tools, fork lifts, etc. ($2M), resulting in a total cost close to $440M as detailed in **Table 2**. Depreciating the $440M of CapEx on a 10-year depreciation schedule, a depreciation cost of $1.47 would apply to each 5.4Wh solid-state, thin-film battery produced.

Factory operating costs, which are defined as costs that do not fall into the categories of depreciation or raw materials, must be considered as well. As mentioned above, the contribution of these operating costs to the total cost of a lithium-ion prismatic battery is approximately 24%. The solid-state, thin-film battery manufacturing processes are inherently cleaner than those of the lithium-ion prismatic battery. The former is subject to fewer regulations regarding handling and disposal of materials (e.g., compact, solid-state targets vs. loose powders, flammable organic liquids or gels) and the estimated operating costs are about 20% of the total solid-state, thin-film battery cost.

Summary and Conclusions

IPS has developed a unique and viable all-solid-state, thin-film battery technology that transcends the domain of micro-batteries and into the realm of high capacity cells to power popular consumer electronics devices, including cell phones and tablets with unprecedented thinness, energy density and safety. Given a sufficiently large thin-film battery manufacturing facility, mass production is now feasible with competitive unit costs. The opportunity comprises the following, substantial and inherent benefits:

- Inherently safe – solid-state, thin-film batteries will not burn or explode when exposed to abusive conditions, since they do not contain any organic electrolyte solvents to provide the necessary fuel
- Energy density of more than 700Wh/liter is feasible, which is 25% higher than current state-of-the-art lithium-ion prismatic batteries (550Wh/liter)
- Cost is less than $1/Wh, very comparable to lithium-ion prismatic batteries
- Solid-state, thin-film batteries maintain their high energy density down to a thickness of 110µm. This frees the designer to use whatever form factor battery is best for his industrial design, rather than use traditional lithium-ion form factor batteries.
- All-solid-state, thin-film batteries automatically provide a “green” manufacturing environment due to the complete absence of organic electrolytes. All process raw materials used in thin-film battery manufacturing are in pressed target form and require no special storage or mixing, nor do they pose any environmental contamination risks.
- All-solid-state, thin-film batteries are built using mature equipment platforms that have support and supply chains already in place
- The IPS solid-state, thin-film battery process consists of only seven steps, reducing manufacturing cycle time and lending itself to large-scale, high-yield, low-cost manufacturing

About Infinite Power Solutions, Inc. (www.InfinitePowerSolutions.com)

Infinite Power Solutions, Inc. (IPS) – a U.S. clean-technology company – is a global leader in manufacturing solid-state, rechargeable, thin-film micro-energy storage devices for embedded applications. Founded in 2001, IPS is privately held with corporate headquarters and volume manufacturing in Littleton, Colo. The company is the only ISO 9001 certified manufacturer of solid-state, thin-film batteries, and its products displace conventional coin cells, supercapacitors, and other micro-battery solutions. THINERGY® Micro-Energy Cell (MEC) products are paper-thin and provide unprecedented power and efficiency in micro-energy storage, uniquely enabling ambient energy-harvesting solutions to create miniature, autonomous, perpetual power supply solutions. MECs serve battery powered consumer applications such as Bluetooth® Smart devices and other wireless sensor nodes, including those enabling the Internet of Things (IoT). MECs also provide backup power for real-time clocks, memory modules, and solid-state drives. By leveraging its core technology and manufacturing expertise, IPS has demonstrated high capacity solid-state battery prototypes that could be configured to power next generation cell phones, tablets and other consumer electronic devices.