As originally published in the IPC APEX EXPO Conference Proceedings.

Digitally Printed Battery: Transitioning from a Traditional Coated Battery Design to a Digitally Printed Battery; Advantages, Challenges and Successes

Dan Tillwick, Solicore, Inc., Lakeland, Florida

Introduction

The company is a producer of thin film batteries of less than 0.45mm in thickness. Battery operated devices have grown smaller and smaller while energy demands have increased as the need for increased functionality has grown. This need has led designers, which would normally use conventionally sized batteries, to consider other types and form factors. Products such as powered display transaction cards, RFID/sensor tags, and medical device patches have created a market for thin film batteries.

The following provides a brief review of battery construction. All batteries are basically made up of an anode (lithium in this case) and a cathode (MnO_2 in this case), separated by a mechanical barrier (separator layer) designed to prevent internal electrical connectivity. The trick with the separator layer is to minimize resistance within the battery by being thin while not too thin as to promote soft shorts, limiting the life of the battery.

The leading candidate for batteries targeting thin film markets is the primary (non-rechargeable) cell based on the conventional 3.0V Li/MnO_2 chemistry, albeit the 1.5V aqueous systems have also been targeted. The Li/MnO_2 battery system can be described simply by the following electrochemical reactions and potential stability window (Figure 1):

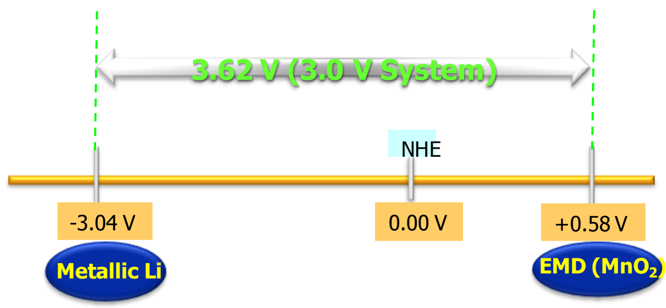

Figure 1.

Anode Half Reaction: $Li \longrightarrow Li^+ + e^-$; $E^0 = -3.04\ V$

Cathode Half Reaction: $Mn^{IV}O_2 + Li^+ \ e^- \longrightarrow LiMn^{III}O_2$; $E^0 = +0.58\ V$

Overall Cell Reaction: $Li + MnO_2 \longrightarrow LiMnO_2$; $V = 3.62\ V$ (Theoretical)

The uniqueness of the 3.0V thin film battery developed by the company is that the separator layer contains a polyimide polymer. This Polymer Matrix Electrolyte (PME) separator layer absorbs electrolyte and acts like a sponge, giving the battery a solid state performance characteristic. In total, the PME serves the dual function of battery separator and electrolyte. This characteristic allows the battery to be thin, flexible, heat resistant (>90°C), and safe (you can cut it in half and nothing comes out).

Figure 2 shows an illustration of the battery.

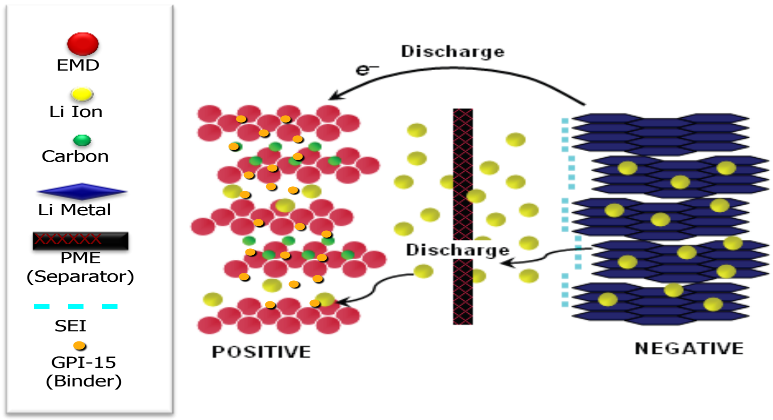

Figure 2.

The current production battery design uses a coating process for creating the cathode and separator layers. Later in the process, an individual piece of solid coil lithium is added, and then finalized into a fully packaged assembly.

The company has developed two alternative technologies to replace the traditional coated manufacturing method: screen printing and piezoelectric inkjet printing of components (Figure 3). Each technology has advantages and disadvantages, serving different markets and applications. Most printing operations are designed to add color or properties with very little consideration for material content. As a result, these printing technologies required modification to achieve the active material weight needed for battery functionality.

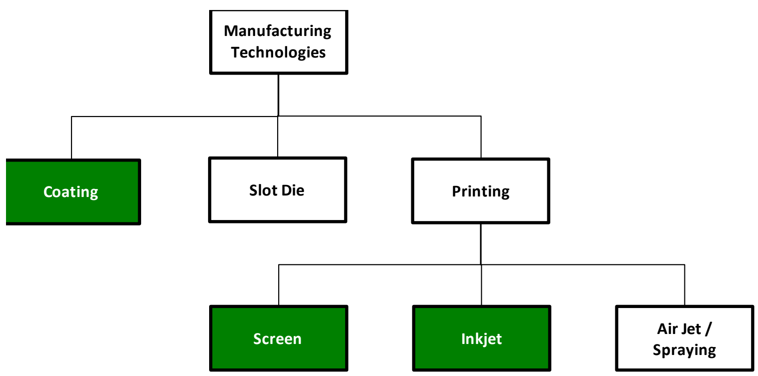

Figure 3.

Table 1 provides a comparison of the resulting battery properties between the coated design (first column) and the digitally printed process (second column). Several characteristics of the printed version of the battery are superior (highlighted in green) to the coated design.

Footprint / Model No.:	SF-2529-14XC	SP-2529-14XC
Product Rating		
Capacity (mAh) - Rated	**14**	**14**
Capacity (mAh) - Typical	**15+**	**15+**
Dimensional Parameters		
Height w/o Tabs (mm)	22.9	22.9
Width (mm)	29	29
Thickness (mm) - Rated	0.45	0.35
Weight (g) - Typical	0.38	0.30
Battery Area - By Rating (cm^2)	6.64	6.64
Battery Area - Active (cm^2)	2.80	2.80
Battery Volume - By Rating (cc)	0.30	0.23
Battery Volume - Active (cc)	0.126	0.098
Capacity Densities		
Specific Capacity - Rated (Ah/kg)	36.84	46.67
Capacity Density - Rated (Ah/L)	46.85	60.23
Capacity Density - Active (Ah/L)	111.05	142.78
Energy Densities		
Specific Energy - Rated (Wh/kg)	110.53	140.00
Energy Density - Rated (Wh/L)	140.54	180.70
Energy Density - Active (Wh/L)	333.14	428.33

Table 1.

The primary reason for the superior printed battery properties has to do with the reduced thickness and weight associated with the printed version of the battery. This reduction in thickness and weight provide for superior energy density within the same capacity battery.

Screen Printed versus Piezoelectric Printed Batteries

Screen printing uses a woven mesh to support an ink blocking stencil that creates open areas of mesh that transfer ink to create the desired resulting image. The ink is pressed through the mesh using a sharp edged blade which moves across the mesh. The advantage of this method is the ability to transfer large amounts of material with relatively large particle size.

The company's screen printed batteries are printed in a batch process onto a receiving aluminum sheet with removable polyester liner (added for strength during the process) and dried in long serial ovens. The cathode is printed first in multiple passes, each followed by a drying process. A separator layer is added (in three layers) and lithium ink is printed and calendared prior to final assembly. All other components are printed, and then packaged in standard packaging.

The piezoelectric printed battery uses a Drop-on-demand (DOD) piezoelectric process. This is an inkjet process which uses a piezoelectric material in an ink filled chamber behind each print nozzle. When a voltage is applied, the piezoelectric material changes shape, generating a pressure pulse in the ink forcing a droplet from the nozzle. Generally, a DOD process uses software to apply up to eight droplets of ink per dot. The major disadvantage of this process is the limited material transfer per application and limited particle size.

The company's piezoelectric printed battery is designed to be printed on a continuous roll to roll basis. The various components are to be printed in multiple layers (or passes) to achieve the required thickness or capacities.

Comparing Methods

In comparing these methods, we should first consider the material transfer characteristics (Table 2).

	Ink Viscosity	Particle Size	Number of Passes Required
Coated	4000-11,000 cps	2-4 µm	One Pass
Screen Printed	250,000 cps	4-6 µm	7 to 10
InkJet Printed	8-10 cps	<0.3 µm	Multiple

Table 2.

As seen in Table 2, the coated battery process is the most efficient. However, it is limited in terms of design flexibility. The most impacting of these limitations is the lack of flexibility to create a different physical size battery with a different capacity.

While it can be done, it requires significant time and cost to modify the process and equipment. This battery size and capacity flexibility attribute is the key benefit of the digitally printed battery processes. While there are still tooling modifications required between sizes for sealing and packaging, the level of complexity and cost is significant lower.

The particle size limitation is only a factor for Inkjet printing. However, this limitation creates significant challenges for ink formulation. A balance must be struck between material delivery and clogging/maintenance of the print head. The smaller particle size can also help in terms of overall energy density of the resulting battery, with a trade-off between current rate limitations and total capacity.

In terms of number of passes required to achieve the design coat weight, the Inkjet requires the most number of passes, followed by screen printed and lastly coated. The number of passes required can negatively affect economics, however only materially with screen printing, since each pass requires a separate drying step and therefore has a significant cost associated with it. While the inkjet process applied to a roll to roll process has significantly lower cost impact due to the number of passes.

Applying the anode is one of the more difficult parts of the coated battery assembly process. Lithium is a soft, flexible metal, and at the thickness used (approximately 40 microns) it is both difficult to manufacture and ultimately to singulate from a coiled roll. This is also a significant limitation when considering alternative sized batteries. The digitally printed battery offers a major advantage in this area. The company has successfully screen printed lithium from an ink. This allows for the necessary size flexibility as previously associated with digitally printed batteries.

There is a collection of other components within the construction of a thin film battery. First and foremost are the current conductors. In the coated battery these are made from a coiled metal (nickel coated copper). The actual anode and cathode conductors are singulated from the coil and mechanically added to the battery structure along with singulated polymer tapes, which act as insulators at the packaging interface of the battery. The digitally printed battery uses printed conductive metals as well as printed insulators. Identifying the best printed conductor from both a point of use and economics standpoint is a challenge. The second significant component is the sealant material. Having an effective moisture barrier is critical to the performance and life of the battery. In a coated battery, the packaging material is built with a sealant layer. In a digitally printed battery, the sealant layer is printed. Getting the right moisture barrier with a printed sealant ink is also a challenge.

Successes

Without doubt, the single greatest technological advancement thus far has been the ability to screen print the anode (lithium). This achievement allows for complete flexibility in dimensional battery characteristics without the concern/difficulty associated with handling coiled metallic lithium.

The ability to formulate inks based upon the coated version of the cathode and PME (separator layer) for application in screen and inkjet printing has also been a great success. The key to this success has been overcoming interlayer adhesion issues that occurred from the multiple layers required to achieve the necessary coat weight.

The printed conductors, insulators, and adhesives that are all functional equivalents to their corresponding traditional non-printed counterparts are also a reflection of the maturing nature of the science that is printed electronics.

The scalability and superior economics of the digitally printed battery combine to form an even larger overall success. While the coated battery process performs well, it has limited scalability and rather fixed economics that have driven the digitally printed battery to become a reality.

Next Steps in Printed Electronics

The company printed battery efforts have demonstrated the ability to use printed electronic concepts on a macro scale. Macro refers to the relatively large amounts of printed material necessary to make a printed battery equivalent to its traditional/coated counterpart. Next steps include aiming for an assembly that today is built with traditionally created individual components, including: an electrophoretic display, 2-layer flexible circuit, as well as capacitors and resistors. These components require significantly less printed material and are more in line with what could be considered the state of the printed electronics art today. The ability to apply printed electronics to these components and further to create a printed integrated assembly will provide the needed scale and cost reduction to justify large scale deployments of new technology that to date has been either too expensive or lacked the production scale to break through the barriers of entry. The list of new technologies is seemingly endless but includes: Powered Display Cards (Secure Access and Financial Transaction), Electronic Shelf Labels, Powered RFID sensors/labels, and Medical Patch Electronics.