Enabling Autonomous Sensing Devices for IoT with Thin Film Batteries

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ABSTRACT

Thin film, solid state, lithium ion batteries present an alternative source of energy to meet the specific demands of applications in the Internet of Things (IoT) space. The features and benefits of a solid state battery operating in the extended temperature range -40°C to + 150°C are presented.

1 POWERING THE INTERNET OF THINGS

The interconnected world of the Internet of Things is creating a demand for billions of sensors in markets as varied as Industry 4.0, self-driving vehicles, agri-tech, healthcare and medical implants, dust computing, environmental and pollution monitoring, etc… As the demand for devices incorporating MEMS and sensors is rapidly multiplying across these applications, so too is the need for low maintenance, long life and minimal size power sources which would remove the need for cabling or regular battery changes. IoT devices offer a different set of battery challenges compared to other electronic devices. They have similar pressures, such as cost and availability, but they also have some specific requirements:

- Small size in both footprint and thickness, towards mm- and sub-mm scale
- Ability to be trickle-charged by an energy harvester
- Longer life span to match those of sensors and microcontroller units (MCU)
- Wide operating temperature ranges
- Ability to be integrated at chips or package level

2 AUTONOMOUS SENSING DEVICES

2.1 Requirements

IoT sensing devices need to transmit data whilst being self-sufficient for power and requiring no external wired power source. Creating autonomous, perpetual beacons using energy harvesting technologies such as vibration, thermal or solar to power the beacon typically requires energy storage as a buffer based on the variability of the energy source. This energy buffer, which may be a battery, a super-capacitor or a Li capacitor, has to meet a number of requirements based on the application such as:

- Charge retention
- Temperature resilience
- Form factor

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- Lifetime
- Safety
- Power requirement (for example to support peak current demanded when transmitting wirelessly over Bluetooth® low energy or LoRaWAN™)
- Sufficient capacity to cope with energy source variability

2.2 The Hidden Cost of Ownership

Machine-to-machine (M2M) connectivity is currently enabled using cabled devices or conventional battery powered devices. Use of these incumbent technologies has associated installation and maintenance costs such as the cost of deploying cables and retro-fitting sensors in old buildings, in addition to changing batteries at regular intervals.

Gartner forecast > 6bn "things" connected by 2020 within cross-industry and vertical-specific businesses [1]. For a typical \$0.20 coin cell, with a typical life time of two years, this is a cost of \$1.2bn every two years just in the cost of the batteries. The cost of deploying resources to change the batteries has to be added. If it takes 10 min for a technician, at an average cost of \$24/h, to replace a battery in a device, this adds \$4 to the real cost of ownership of this battery.

Wired solutions can cost >\$300 per metre to run through existing infrastructure, in addition to the opportunity costs such as losses due to shut down.

With wireless solutions, battery replacement and failure costs drive up the cost of ownership as the system ages due to unpredictable labour and logistics costs.

2.3 Industrial IOT

The industrial sector is a prime example of sector which has embraced automation for decades and Industry 4.0 is now deploying large number of sensors for full factory automation, data acquisition, testing, failure detection, predictive maintenance, asset monitoring, supply chain traceability and security applications.

For many industrial applications, it is often impractical and sometimes impossible for sensors and devices to be placed in:

- Difficult-to-reach places (*e.g.* downhole mining, military, geophysics, in fields).
- Hot or cold environments (machinery, engines, pipeline inspection gauges).
- High vibration environments (drilling, machinery).

Enabling operation at high temperature is a particularly tough requirement with many pieces of machinery functioning at temperatures well in excess of 100°C, for example in textile, plastic packaging, tarmac transport and storage, engines, drilling.

Currently deployed batteries include polymer or liquid electrolytes which limit the operating temperature window and may leak with high vibrations. Industrial cylindrical primary batteries are available which may operate to 160°C, but these are quite bulky (AA type). Some primary coin cells operate up to 125°C, but are not rechargeable. Rechargeable coin cells often have a 70°C top operating temperature, too low for some industrial applications.

3 SOLID STATE BATTERIES

3.1 Features

Solid state batteries provide an alternative energy source consisting of all-solid components usually deposited by evaporation or sputtering.

Thin film all solid state lithium ion batteries have significant advantages when applied to distributed wireless sensor network applications. Their low leakage current, at the nA-scale, allows for longer term storage and operation whilst supporting efficient trickle-charging from usually intermittent, low current level energy harvesting sources. They do not consist of liquid or polymer electrolyte making them a safer lithium ion battery option. They can be manufactured in small size and thickness (below 1 mm) for insertion in miniaturised devices and integration with other electronic components enabling the end product to be kept as small as possible. Finally, the solid state battery components have low thickness (several microns), allowing for high ionic and electronic conduction to yield relatively high power and pulse currents which may for example power Bluetooth® low energy transmissions.

3.2 Stereax^{TM} P180 – Extended Temperature Range Solid State Battery

To respond to the harsh environmental demands posed by Industry 4.0, Ilika has developed a range of small size solid state lithium ion batteries, named Stereax, that can operate and be stored in the extended temperature range from -40°C to +150°C. This solid state battery is produced by Physical Vapour Deposition and sputtering and constitutes of a $LiCoO_2$ cathode and an amorphous Si-based anode. Encapsulation materials were selected to allow operation at extreme temperatures. A diagram of the battery's architecture [2] is shown in Figure 1.

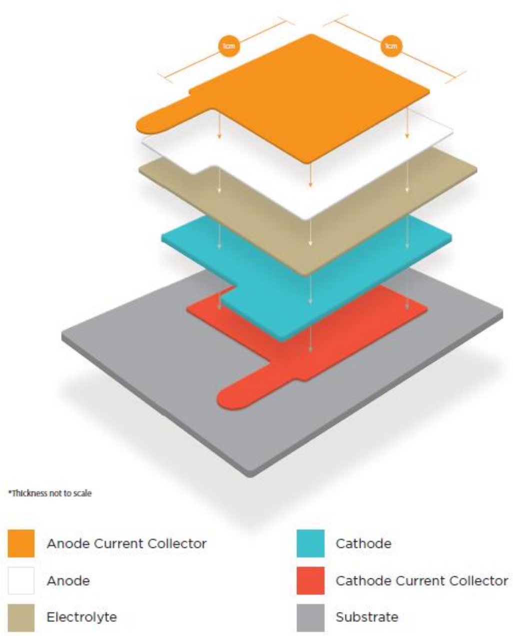

Figure 1: Expanded construction view of Stereax P180 solid state battery.[2]

With a capacity of 180 μAh in the voltage range 3 to 4 V, it can be cycled 1000's of times, depending on temperature. At the high end of the temperature range, at 150°C, this micro-battery can provide enough current for radio transmission without need for an additional capacitor or supercap. At the low end of the temperature range, it can cycle 1000's of times with excellent capacity retention.

4 MATERIALS DISCOVERY

Ilika has developed a patented High Throughput Physical Vapour Deposition (HT-PVD) technology platform to discover and optimise new materials up to 100 times faster than traditional methods. Ilika has designed new materials for over a decade, including for the automotive, aeronautical and electronic components sectors.

Combinatorial synthesis of thin films using proprietary evaporation methods [3], and high throughput characterisation and screening, has enabled Ilika to optimise the component materials, and the combination of these materials, in solid state batteries. This approach has previously been validated using benchmark solid state electrolytes materials such as $Li_{3x}La_{2/3-x}Ti_{1/3-2x}O_3$, "LLTO" [4]. The advantages of this approach, particularly with regard to lithium-containing materials, was more recently [5] applied to cathode / electrolyte interface modification, and is exemplified for cathode, anode, and conventional and new solid electrolyte materials. For example, the solid electrolyte "LiBSiO" was deposited for the first time in a thin film form compatible with the production of solid state batteries. The material has been optimised using high throughput materials libraries [6]: preliminary exploration of the Li_2O-B_2O_3-SiO_2 phase diagram has revealed that when deposited at 225°C, the materials family is amorphous and yields ionic conductivities of up to *ca.* 5×10^{-6} Scm^{-1}, for 76 at. % Li, ratio B/Si ~ 1 deposited in O_2, as shown in Figure 2. The high-throughput methodology has allowed to characterise and screen these phases in details, with results to be published [7].

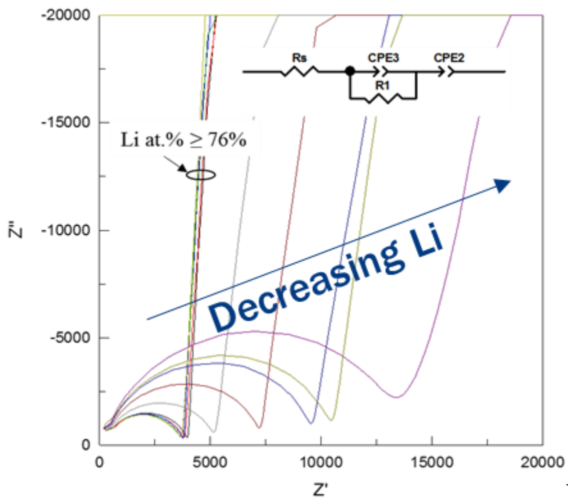

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Figure 2: Nyquist plot of LiBSiO with variable Li content.

5 OTHER APPLICATIONS

Solid batteries may be used in many areas of IoT requiring long life, small size energy sources

In the healthcare sector, Medtech is changing to embrace the interconnectivity of IoT for more proactive patient health management. This has created a demand for remote patient monitoring, with devices needed to monitor and report vital data to central healthcare providers. These smart devices may by external (low power wearables) or internal, implantable or ingestible devices that may be used to collect patient data or support drug delivery. In terms of battery requirements, the demand from Medtech is for long-life, miniature-size power sources, in the mm-scale.

In addition to Industry 4.0, several sectors are also in need for extended temperature range batteries such as the Stereax P180, including Smart Vehicles (tyre pressure monitoring systems, battery pack temperature control, powertrain fluid temperature, emission control); Infrastructure (pipeline monitoring, structural monitoring of bridges …) and Aerospace.

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