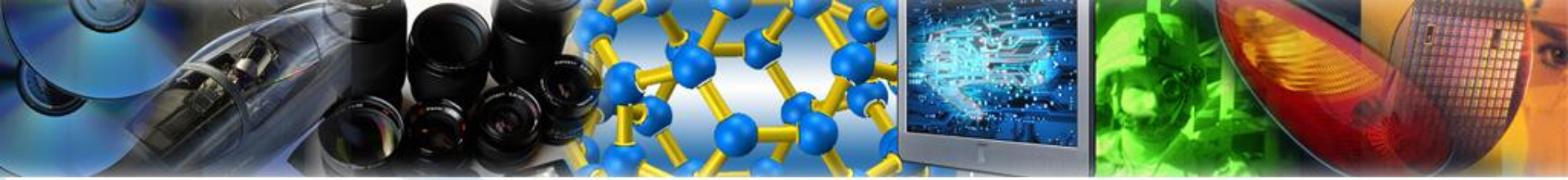
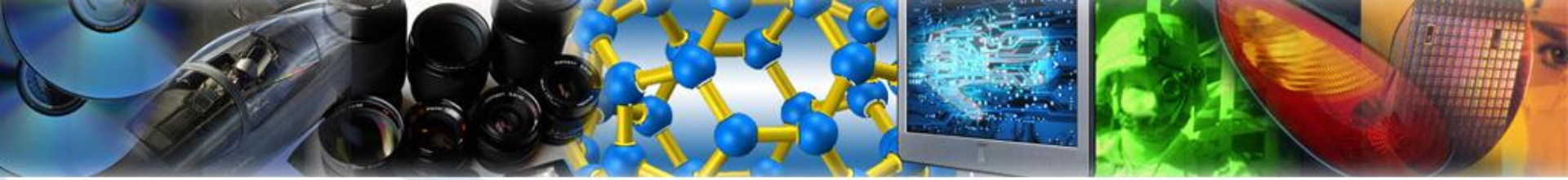


Energy Storage in Thin Sputtered Films

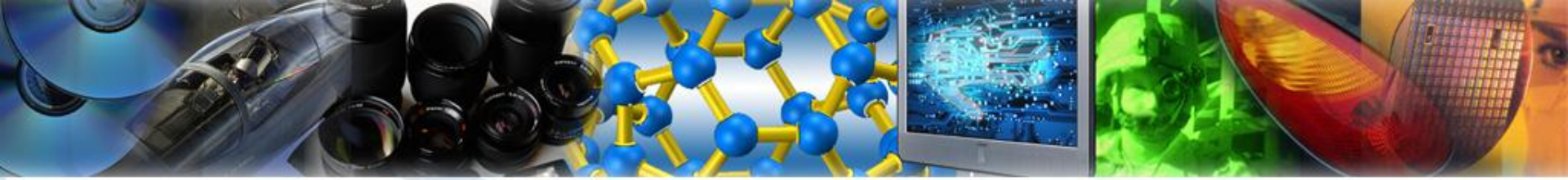
Materials Group, Ceramics Manufacturing Division

J.R. Gaines, Jr., Technical Director



J.R. Gaines Bio

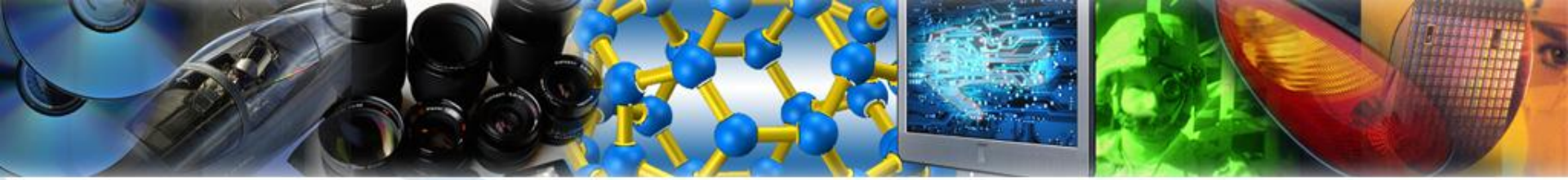
- Career in advanced materials development, manufacturing and commercialization
  - Temperature sensors
  - High Tc Superconductors
  - Ceramic powders, sputter targets
  - Thin Film Batteries



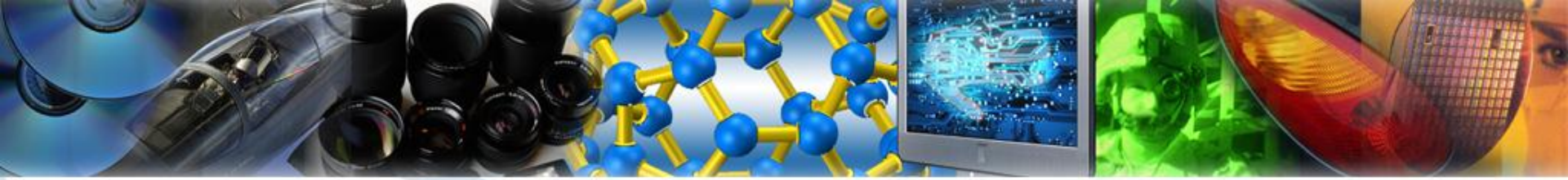
www.lesker.com sales@lesker.com

Kurt J. Lesker Company

1.800.245.1656 412.387.9200

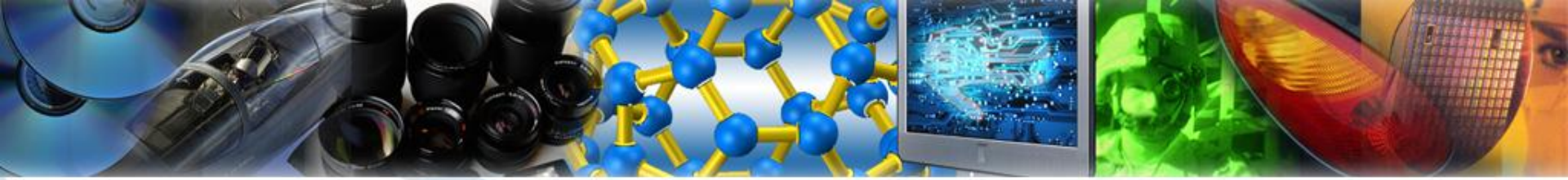


- **Three Global Headquarters**
- **Multiple Strategic Satellite Offices**
- **Six Global Distribution Centers**

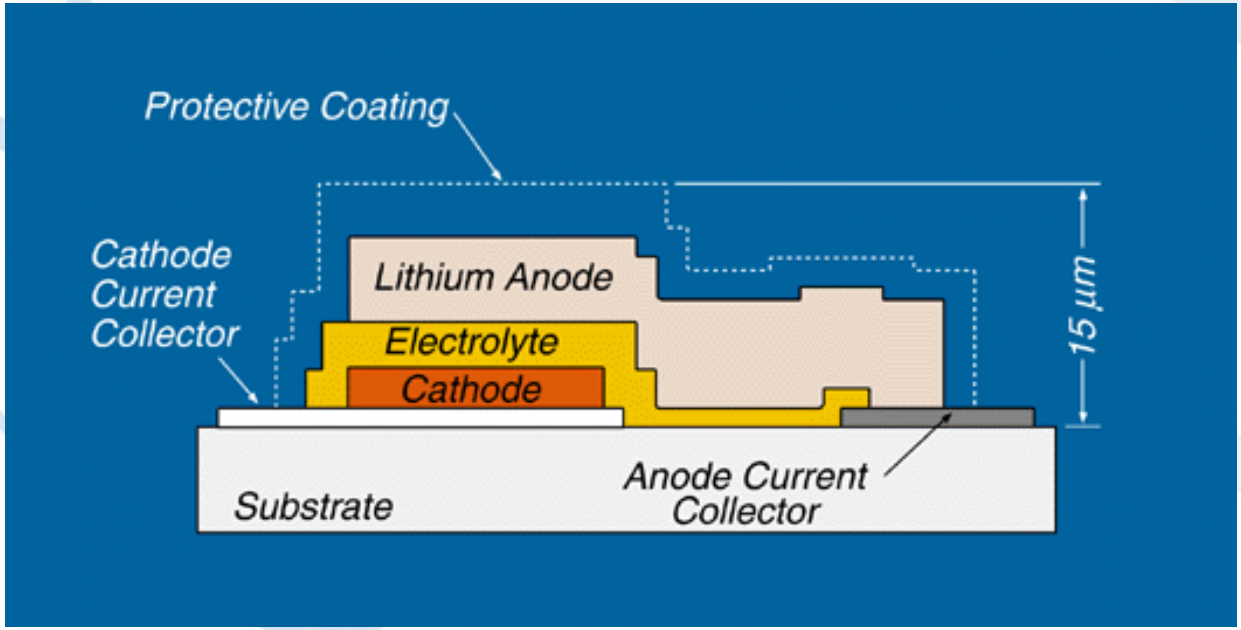


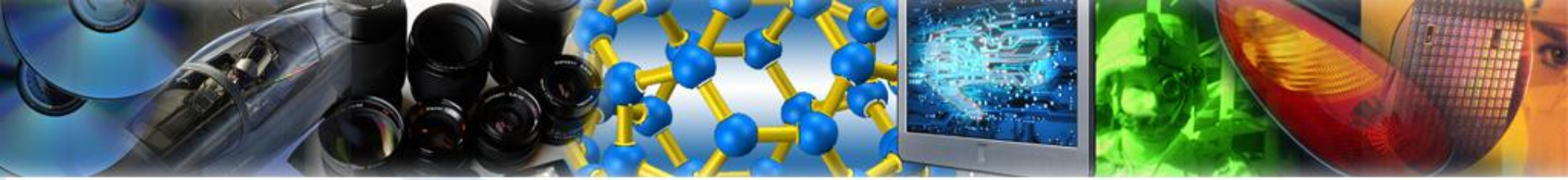
Thin Film Batteries

- What is a thin film battery?
- How is a thin film battery made?
- How does it compare to conventional batteries?
- What are it’s commercial applications?
- What is KJLC’s position in this market?



- ‘THIN’ means the active thin film layered stack is 15 – 20 microns thick
- (Add the thickness of the substrate/host)





How a TFB works (Dudney, ORNL)

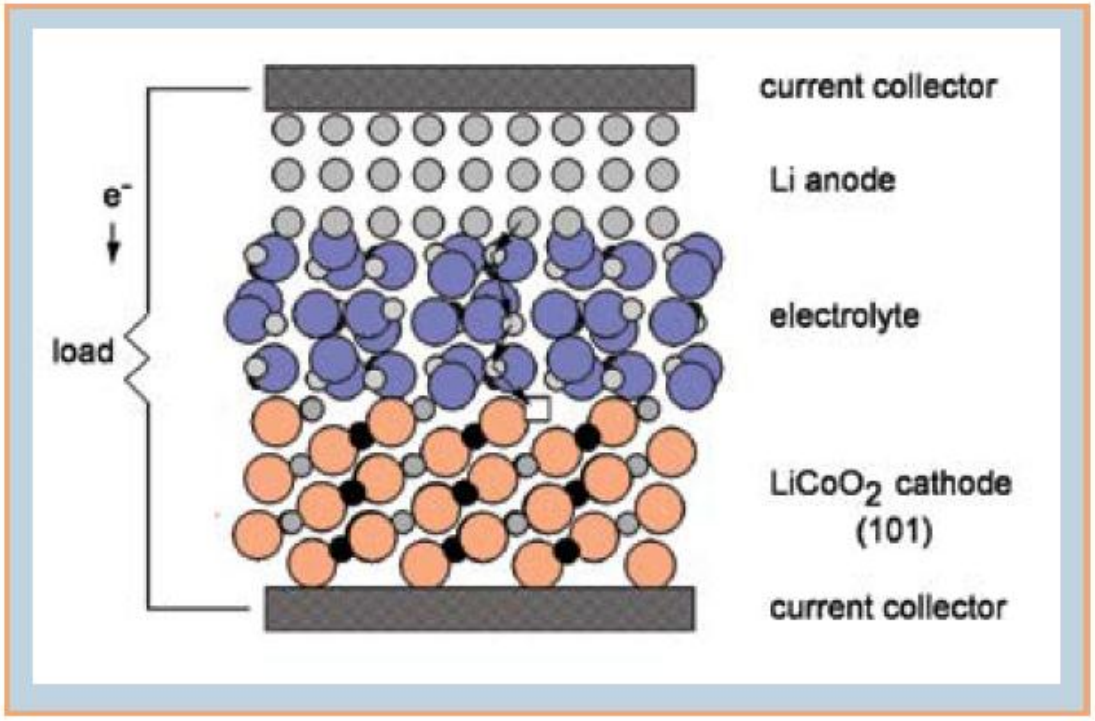
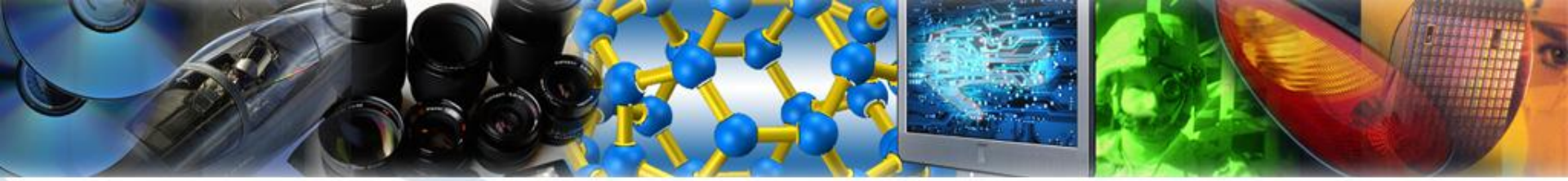
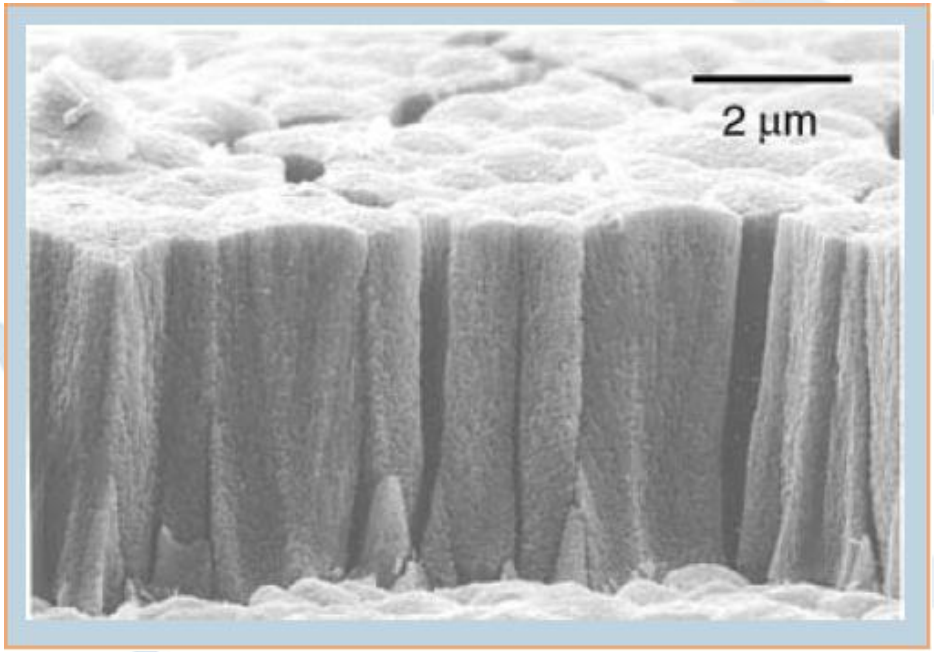


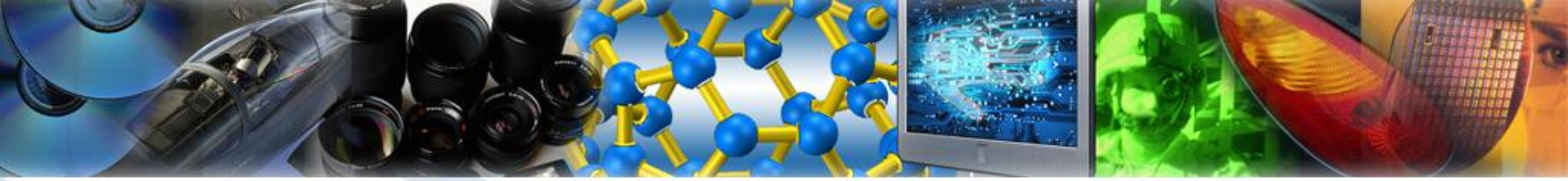
FIG. 2. *Schematic illustration of a thin film battery. The arrows indicate the discharge reaction where a Li ion diffuses from the lithium metal anode to fill a vacancy in an intercalation compound that serves as the cathode. The compensating electron is conducted through the device.*



- Unique microstructure that is oriented and dense



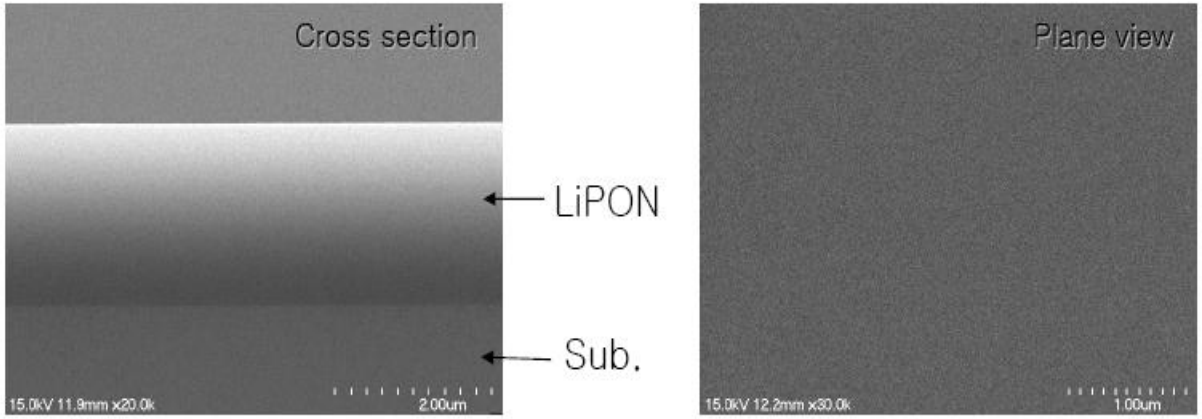
Lithium cobalt oxide after high temp anneal



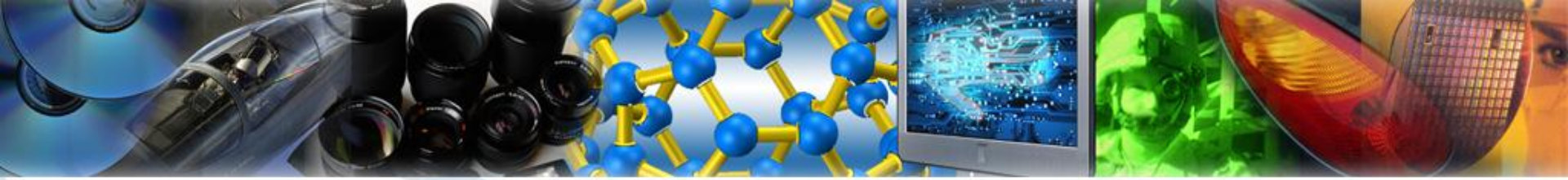
Unique Electrolyte that is VERY THIN
and pore-free to promote transport

SEM images : LiPON Thin Film by Nitrogen Reactive Sputtering

World No.1 in Thin Film Battery



Glass-like morphology with smooth surface.



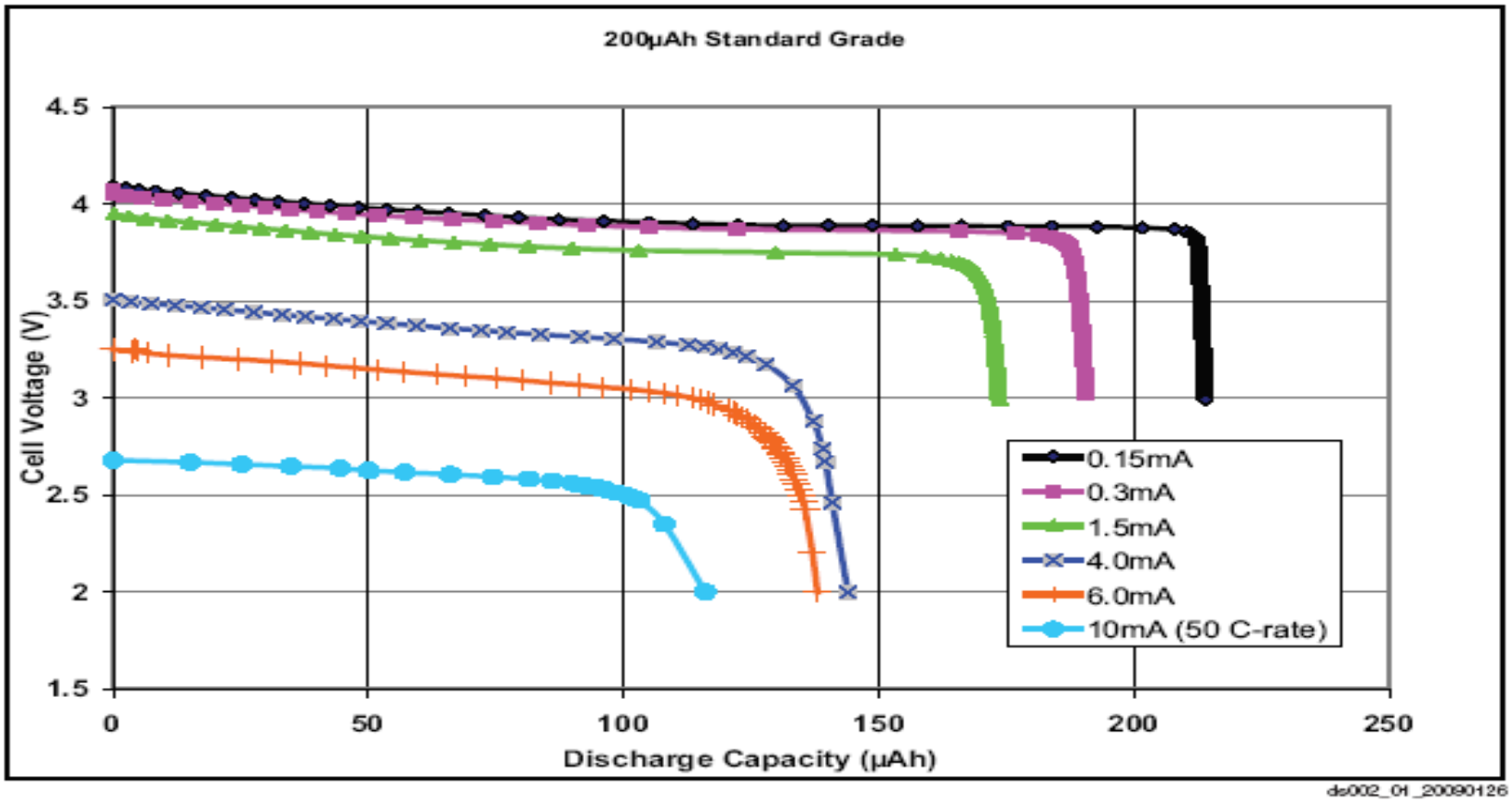
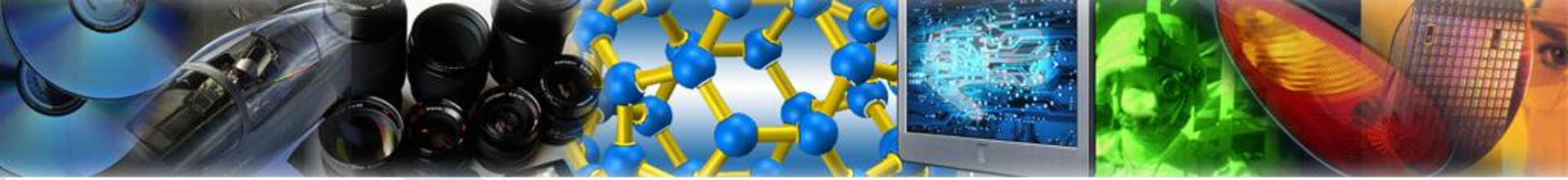
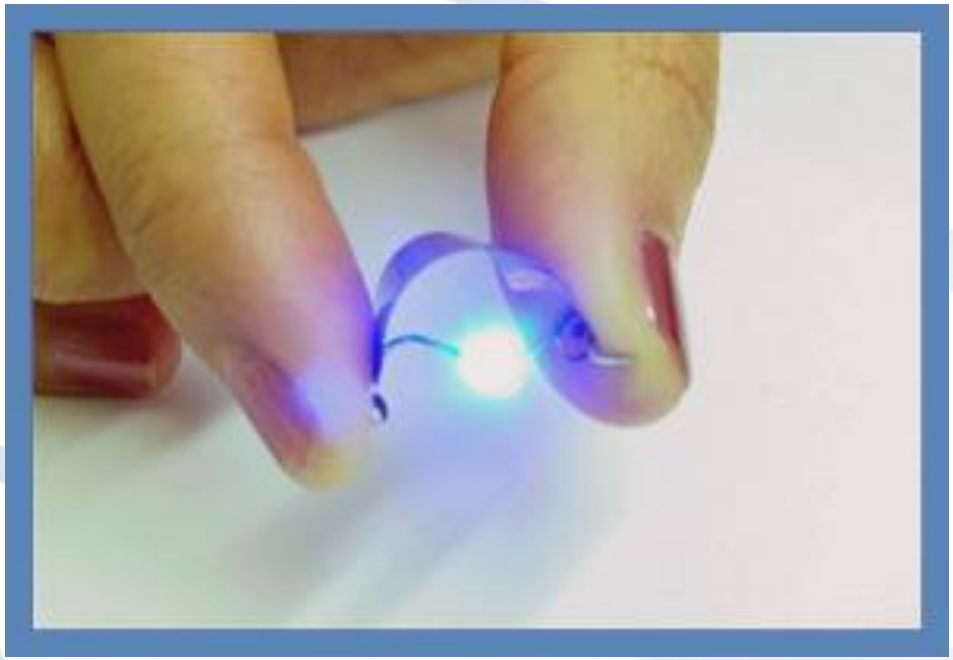


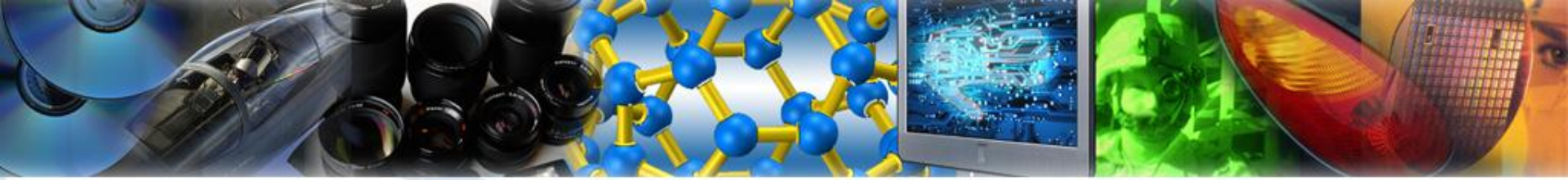
Figure 1: **Typical Discharge Curves @25°C (200 µAh Standard Grade Cell)**



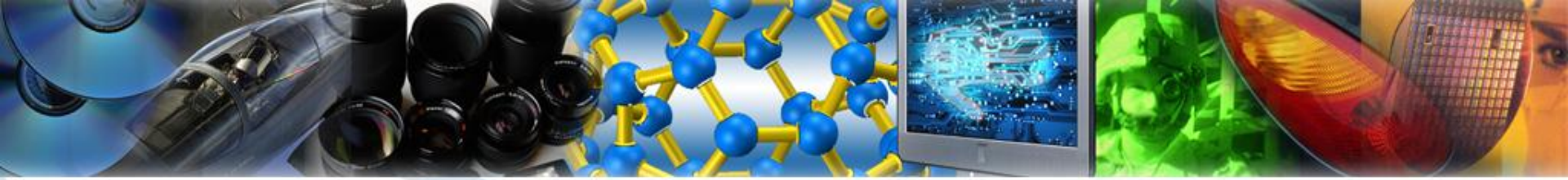
- Thin AND flexible



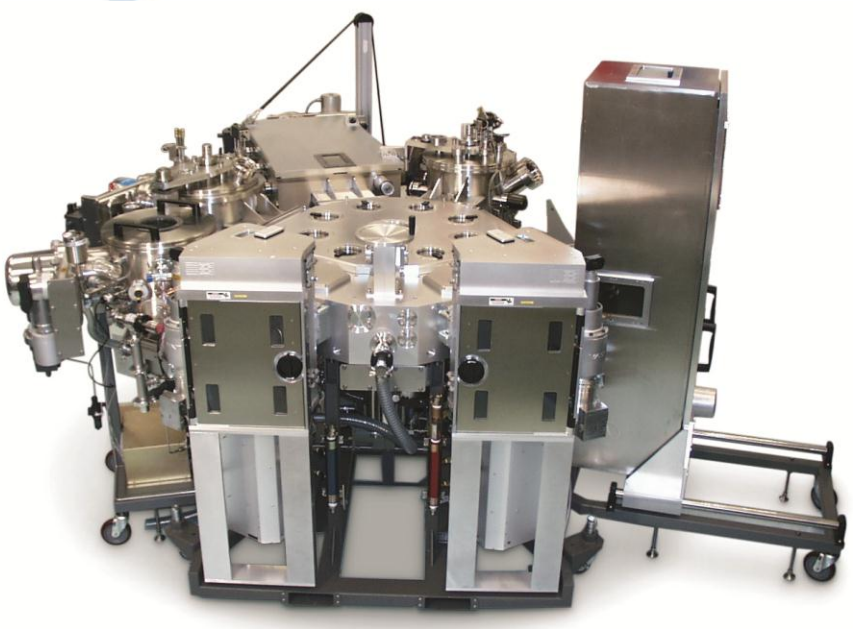
Front Edge Technology's Flexible TFB in action



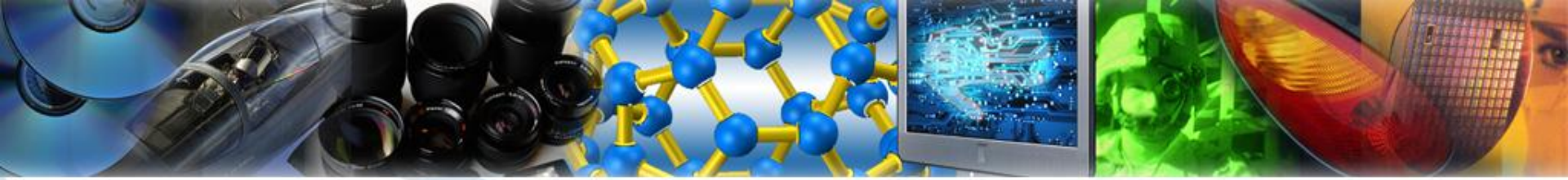
- Unique Technical Features
  - ‘Perpetually’ rechargeable +70,000 cycles demonstrated by ORNL
  - Operating temp range -40 to +200 C
  - Self discharge <1% per year (studied over 6 years)
  - Fast recharge to 90% in less than 10 min
  - Highly embeddable and safe



TFB Manufacturing Process

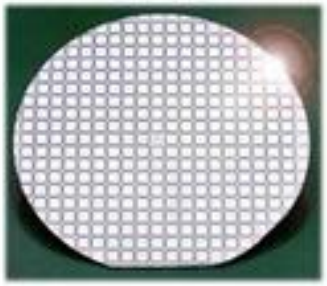


- Deposit metal electrode on substrate (DC sputter)
- Deposit cathode, LiCoO2 (DC sputter)
- Break vacuum and anneal
- Deposit electrolyte, Li3PO4 (Rf sputter)
- Deposit anode layer, Li or other, (evaporation)
- Deposit top metal electrode (DC sputter)
- Encapsulate the battery



TFB Integration with Host

EnerChip Silicon Wafer



Diced

EnerChip Bare Die

Packaged

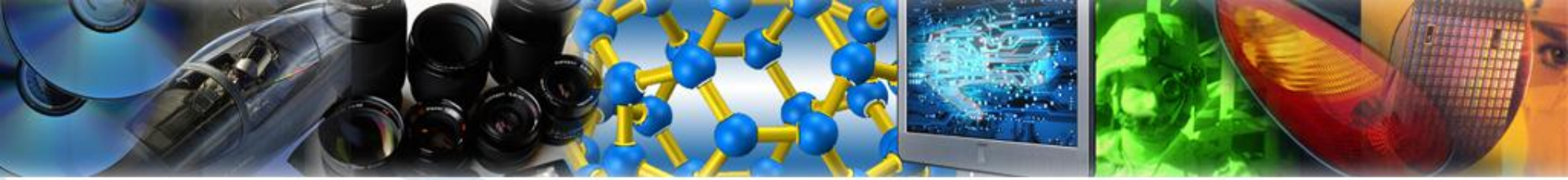
EnerChip IC Package

To Surface Mount Machine

To Reflow Solder

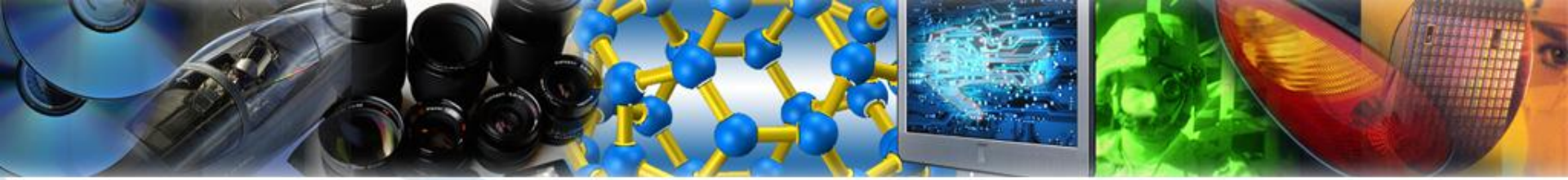
Final Assembly

EnerChips on Board



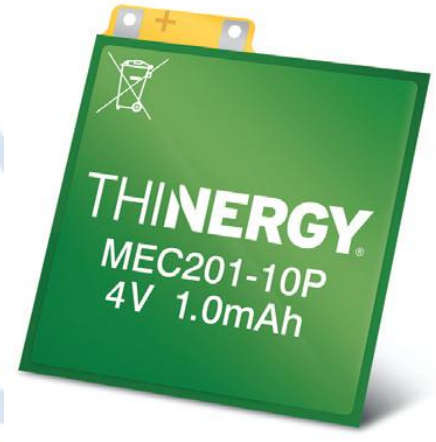
Why is there a market for solid state thin film batteries?

- The perpetually shrinking wireless gizmo
- Limits on the ‘shrink-ability’ of conventional energy storage technologies
- Safety concerns with flammable electrolytes
- ‘Green Battery’ where device life = battery life



- Near term applications include
  - Wireless sensors
  - CMOS back-up
  - SRAM back-up
  - ‘Energy Harvesting’ systems
  - Smart Card
  - Active RFID tags
  - Therapy delivery systems

Commercial Products (IPS)



Actual size 1 x 1 x 0.007”

Capacity 1 micro Amp Hour

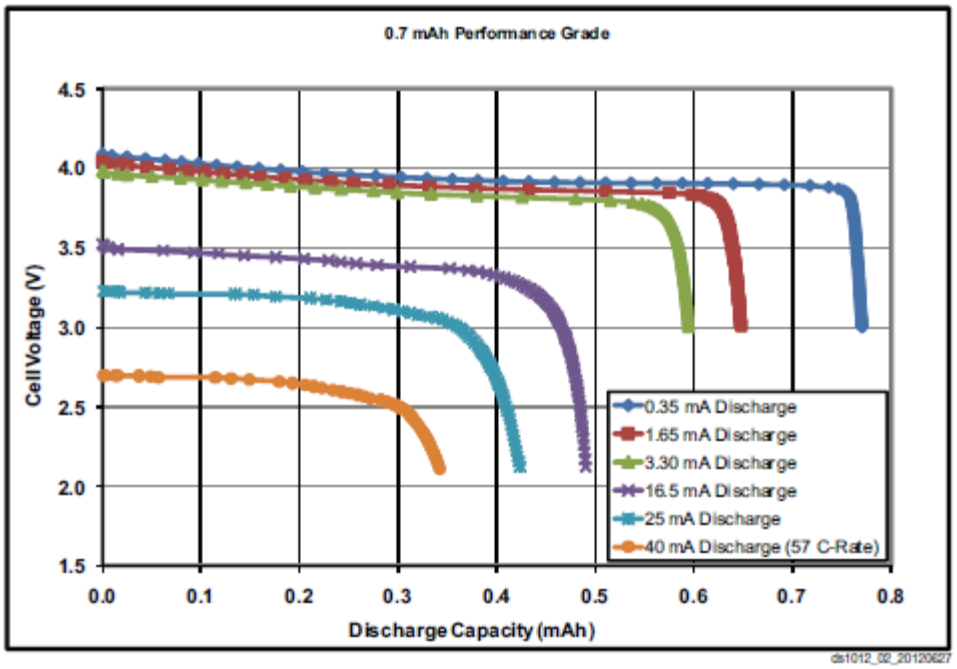
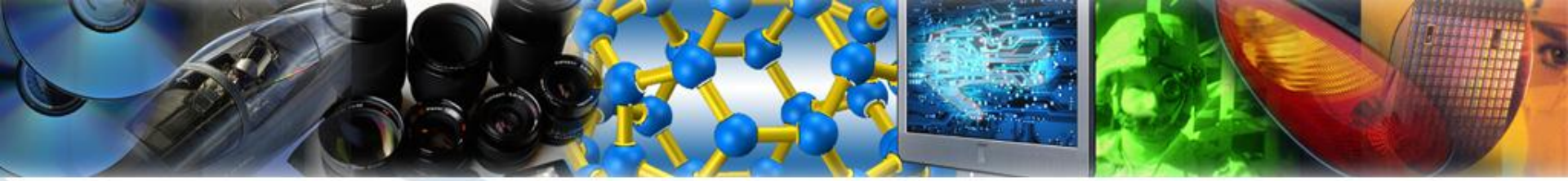


Figure 2: **Typical Discharge Curves @25°C (0.7 mAh Performance Grade Cell)**



ST Micro's 'EnFilm'

EFL700A39

EnFilm™ - rechargeable solid state lithium thin film battery

Datasheet – preliminary data

Features

- All solid-state
- Ultra thin
- Fast recharge
- Long cycle life
- RoHS compliant
- UL file number: MH47669

Applications

Device is intended to be used in following applications:

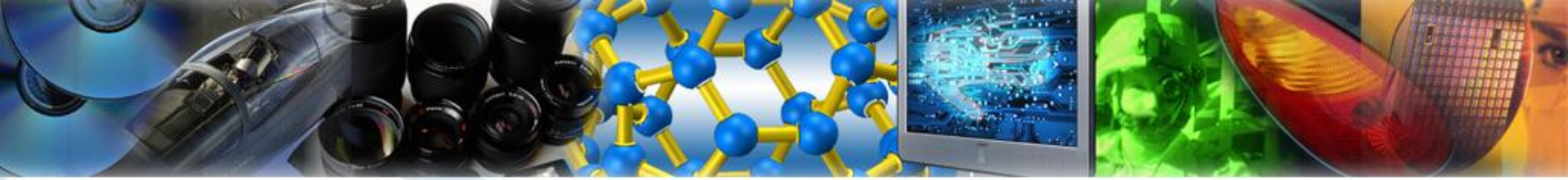
- Sensors and sensor networks
- Smart card
- RF ID tags
- Energy storage for energy harvesting devices
- Non implantable medical applications
- Backup power

Description

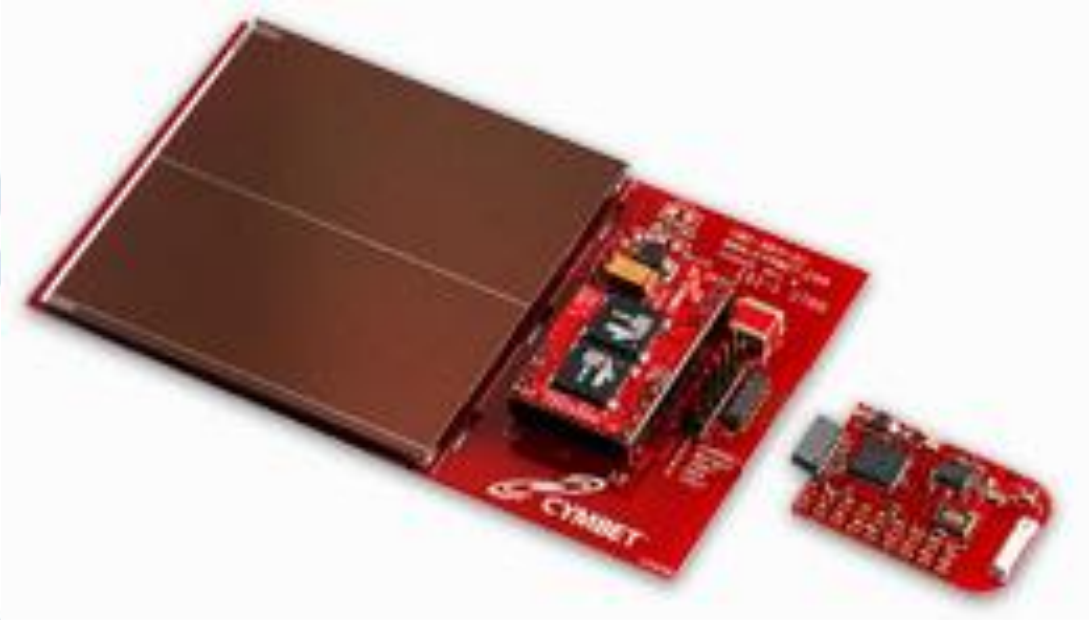
The EFL700A39 is a thin film rechargeable lithium battery. The battery has a $LiCoO_2$ cathode, LiPON ceramic electrolyte and a lithium anode. This device has a footprint of 25.4 x 25.4 mm.

Table 1. Device summary

Symbol	Value
Capacity	0.7 mAh
$V_{nominal}$	3.9 V
V_{op}	3.6 to 4.2 V
R_{int}	100 ohm
I_P	10 mA
Dimension	25.4 x 25.4 mm
Thickness	200 µm



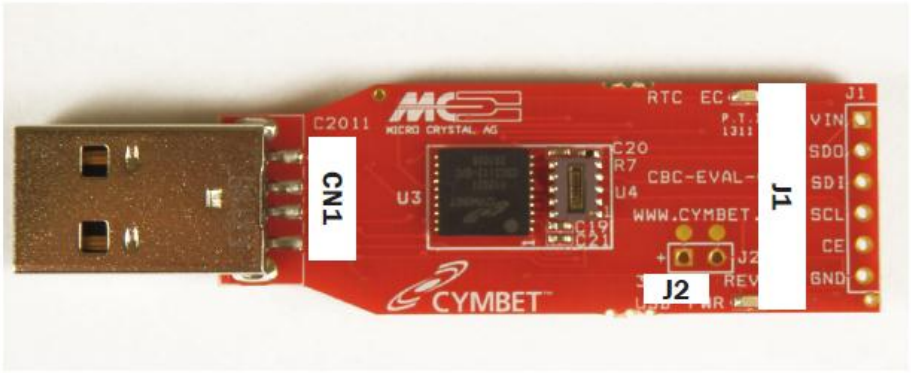
- Cymbet/Texas Instruments Energy Harvesting Platform

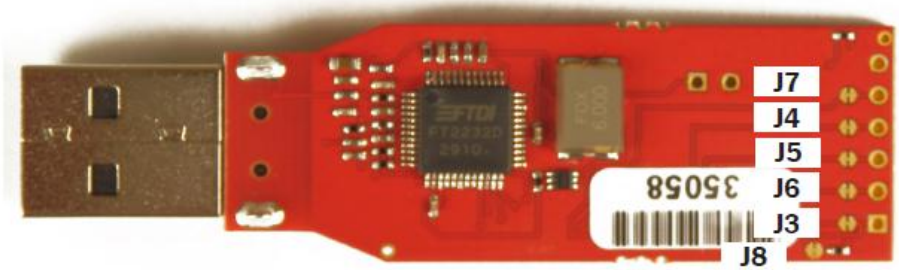


Demonstration Platforms

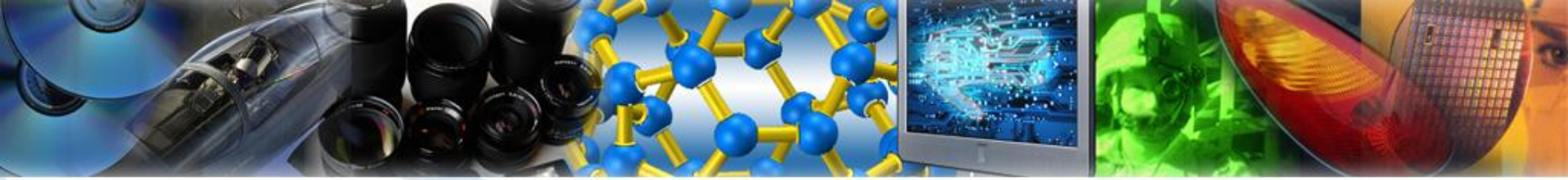
CBC-EVAL-06 EnerChip CC RTC Evaluation Kit

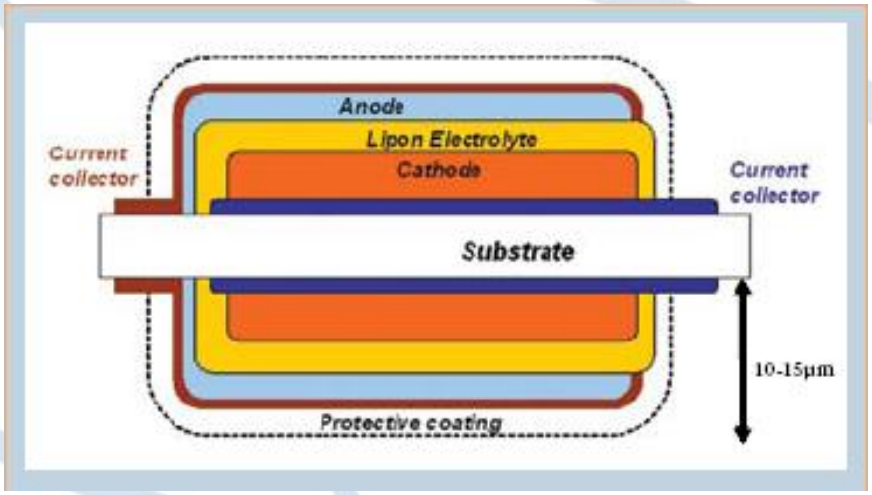
CBC-EVAL-06 Module Connector, Jumpers, and Test Points





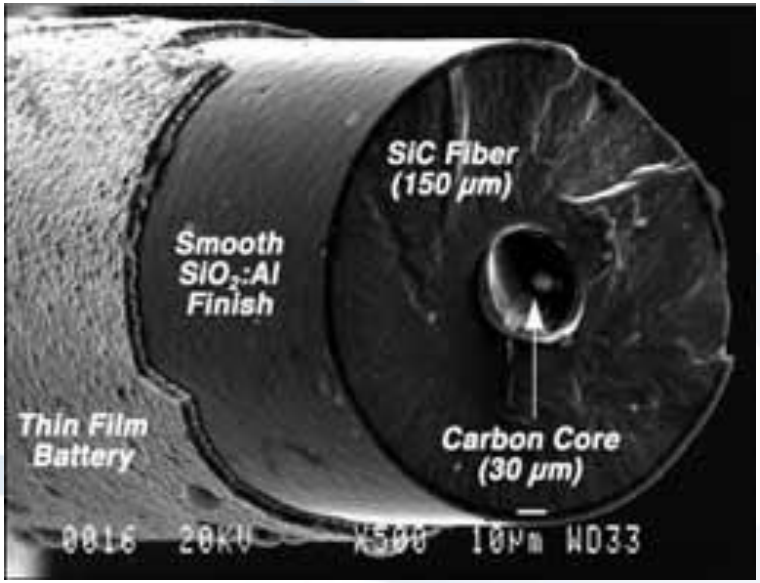
- Infinite Power Solutions Applications Development Kit



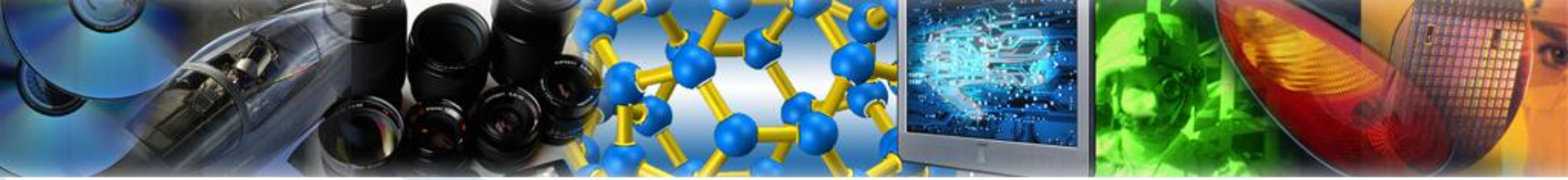


Two-sided architecture

Conformal feature of TFB's

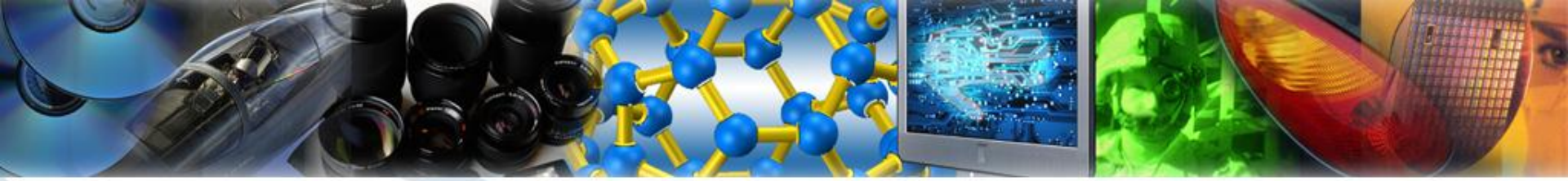


Experimental TFB on fiber



Next Generation Applications

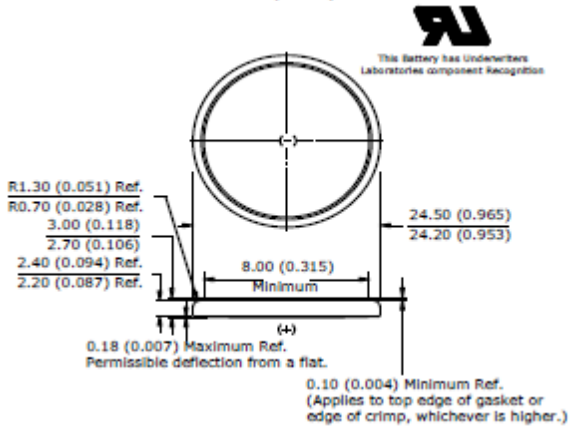
- Smart Phones
- Tablet computers
- Laptops
- Solar panels
- Smart clothing



Coin Cell Performance

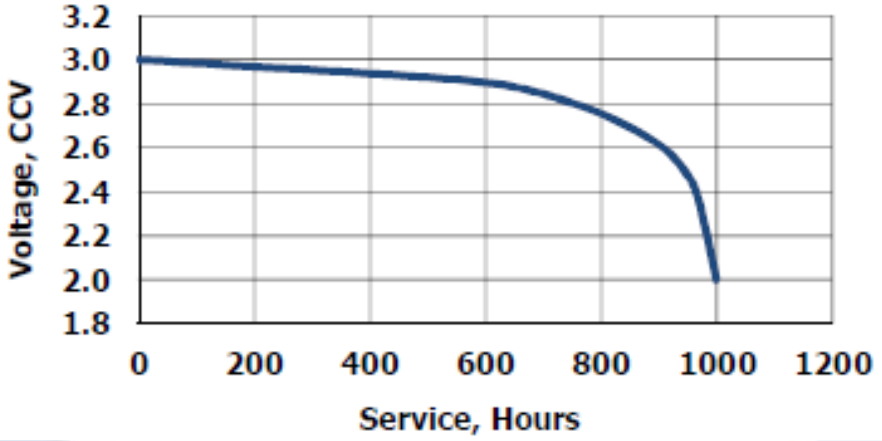
ENERGIZER CR2430

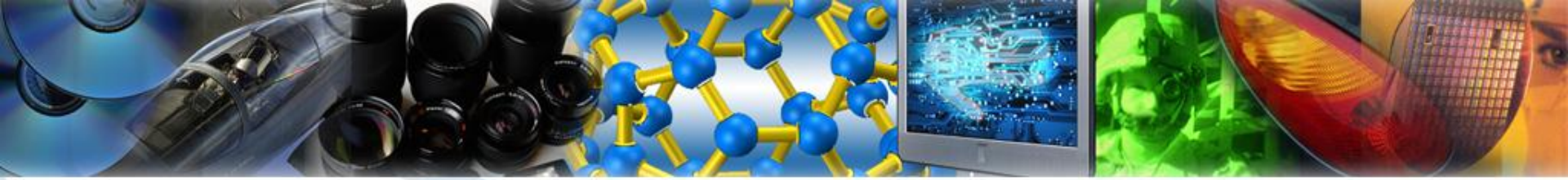
Capacity 290 mAh



Typical Discharge Characteristics

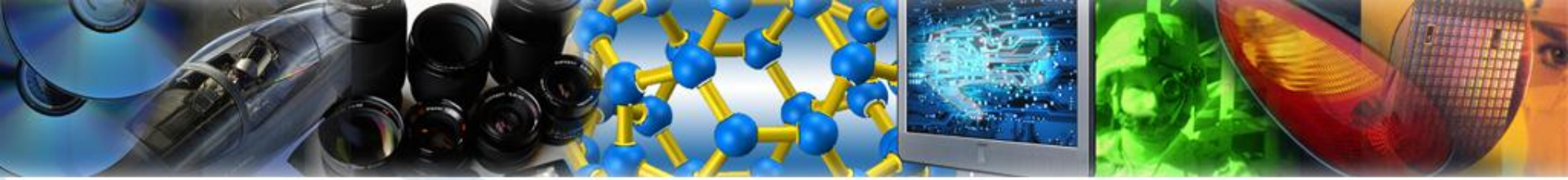
Load: 10K ohms - Continuous
Typical Drain @ 2.9V: 0.29 mA





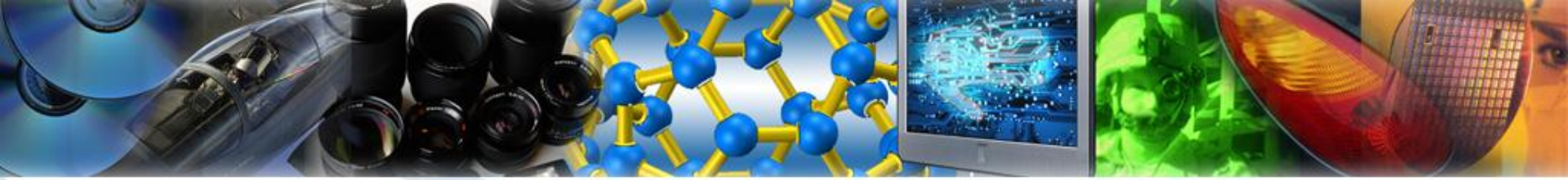
- Other ‘thin’ batteries
  - Printed Batteries

Power Paper 1.5v Primary Battery

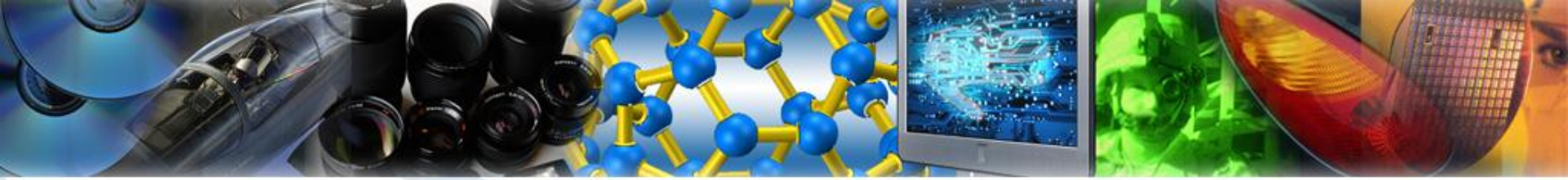


- Performance of TFB Vs Printed Batteries

	Power Paper STD-3 Premium (primary battery)	***IPS THINERGY MEC101 (secondary battery)***
Outline Dimensions	39 x 39 mm	25 x 25 mm
Nominal voltage	1.5v	3.9v
Nominal Continuous Current	0.5 mA	40mA
Nominal Capacity	30mAh	1mAh
Shelf life	3 years	10 years
Self Discharge Rate	20% p/year	1% p/year



- Development and Commercialization of Thin Film Batteries
  - ORNL developed the technology and nucleated the commercialization process
  - Companies formed specifically to manufacture and commercialize TFB
  - Existing companies have added TFB manufacturing and commercialization to their product line



- **Early publications attracted commercial interests:**

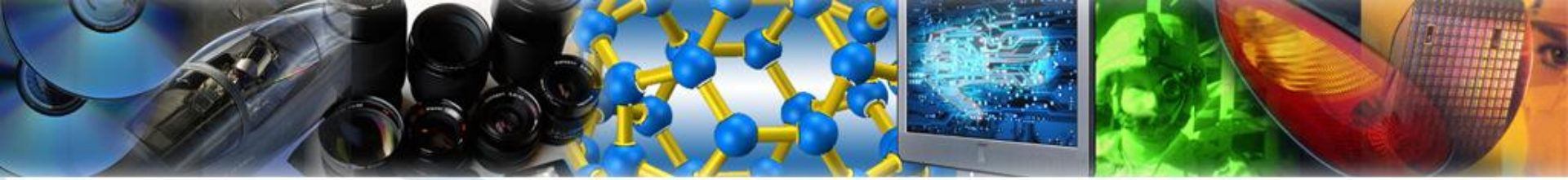
- J. B. Bates, G. R. Gruzalski, N. J. Dudney, C. F. Luck, and X. Yu, "Rechargeable Thin-Film Lithium Batteries," Solid State Ionics 70/71, 619 (1994).

- J. B. Bates, G. R. Gruzalski, N. J. Dudney, C. F. Luck, and X. Yu, "Rechargeable Thin-Film Lithium Batteries," p. 213 in Proceedings of Eighth Electronic Materials and Processing Congress, ed. by S. T. Rao, ASM International, Materials Park, Ohio, 1994.

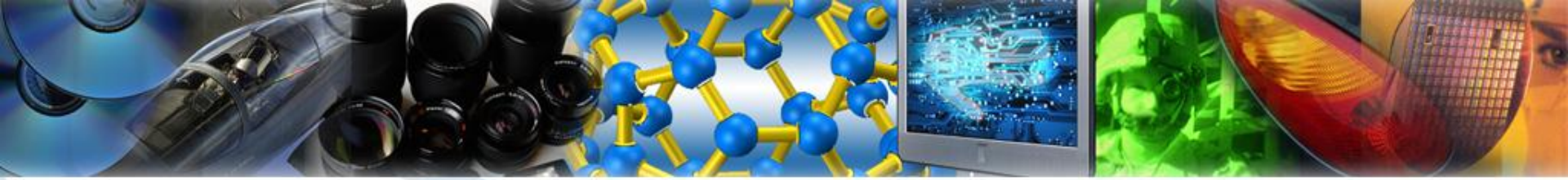
- J. B. Bates, G. R. Gruzalski, and C. F. Luck, "Rechargeable Solid State Lithium Microbatteries," p. 82 in Proceedings of IEEE Workshop on Micro Electro Mechanical Systems, The Institute of Electrical and Electronics Engineers, Piscataway, New Jersey, 1993.

- J. B. Bates, N. J. Dudney, C. F. Luck, B. C. Sales, R. A. Zuhr, and J. D. Robertson, "Deposition and Characterization of Li2O-SiO2-P2O5 Thin Films," J. Am. Ceram. Soc. 76, 929 (1993).

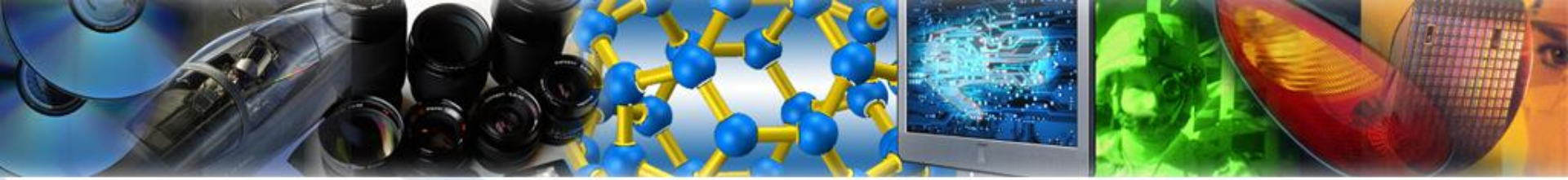
- J. B. Bates, G. R. Gruzalski, N. J. Dudney, C. F. Luck, X. Yu, and S. D. Jones, "Rechargeable Thin-Film Lithium Microbatteries," Solid State Technology 36 (7), 59 (July 1993).



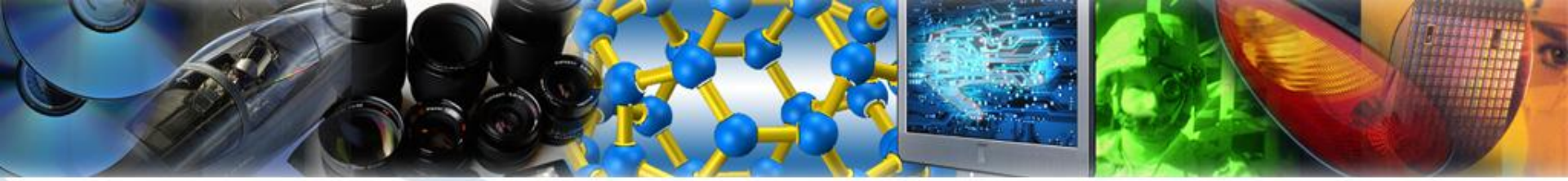
- ‘Pure Play’s in Thin Film Batteries
  - Infinite Power Solutions (Colorado)
  - Cymbet (Minnesota)
  - Oak Ridge Micro-Energy (Tennessee)
  - Planar Energy Devices (Florida)
  - GS Nanotech (S. Korea)



- Companies that added TFB
  - Front Edge (California)
  - ITN Energy Systems (Colorado)
  - Excellatron (Georgia)
  - Schmid (Germany)
  - ST Micro (France)
  - Others who can not be named

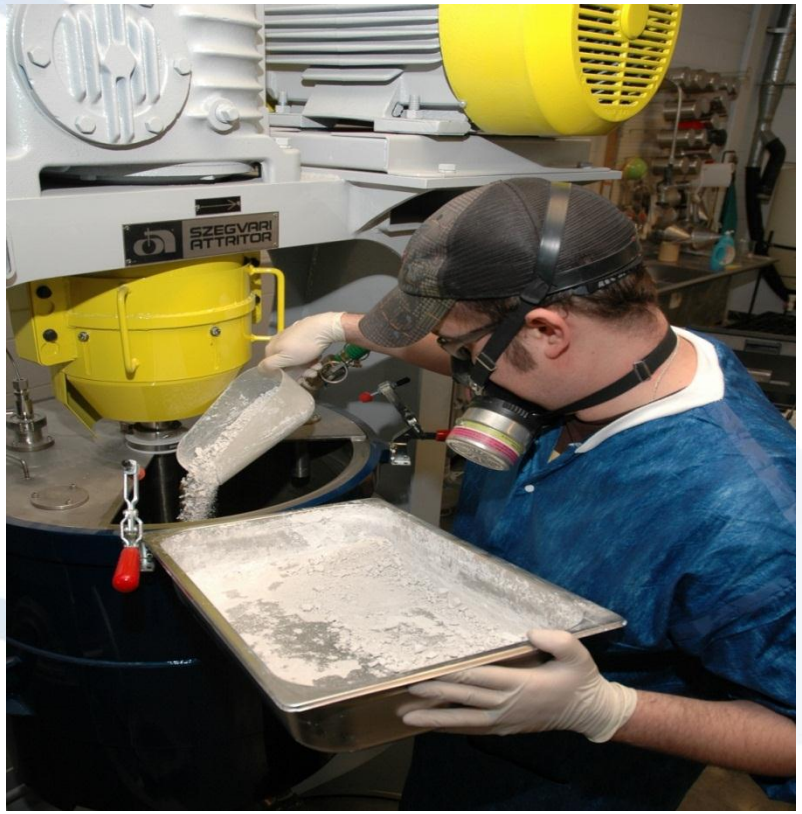


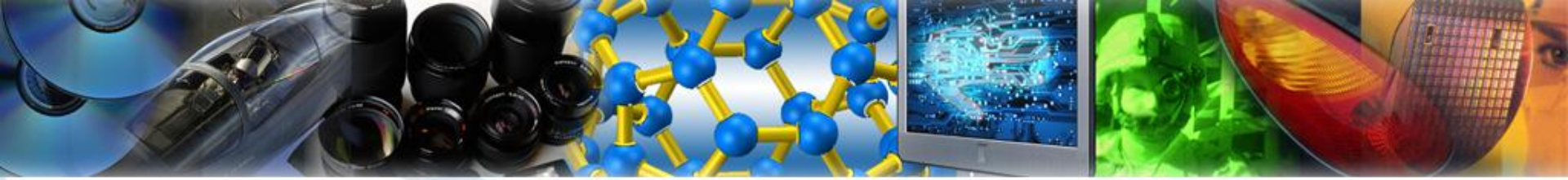
- Sputter target evolution
  - Refinement of target chemistry to enhance manufacturing
    - Compensation for Li losses in processing
    - Electrical conductivity of LiCoO2 cathode target
    - Phase and chemical purity of Li3PO4 targets
  - Growth in target size since 1994’s from 2” diameter to 1 sq meter in 15 yrs



$LiCoO_2$ & Li_3PO_4 Powder

- Batch size ~45 kilos
- Dedicated mixing/milling equipment to avoid cross-contamination



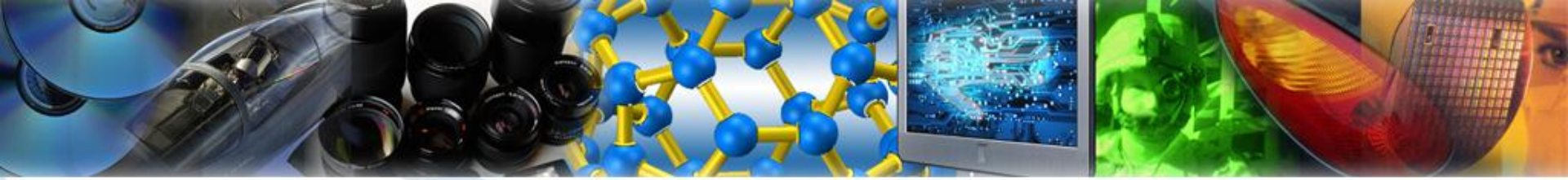


Sintering

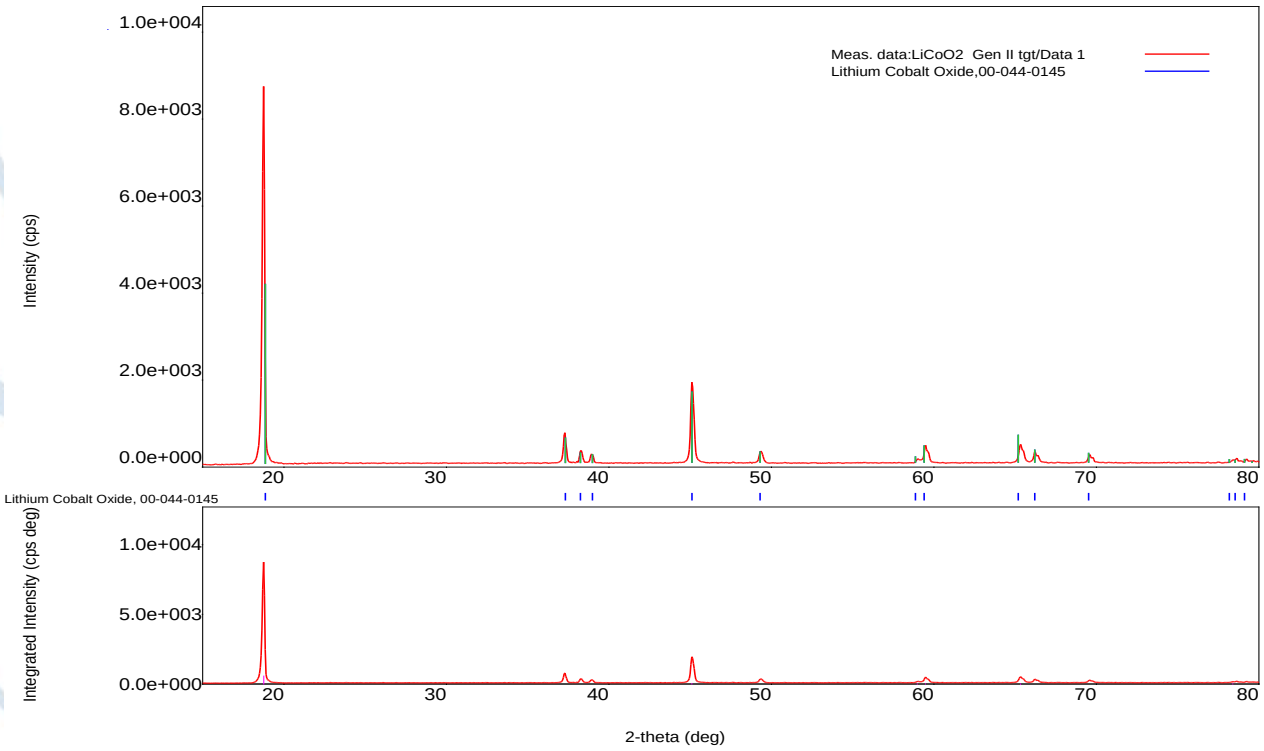
(330mm OD Blank)

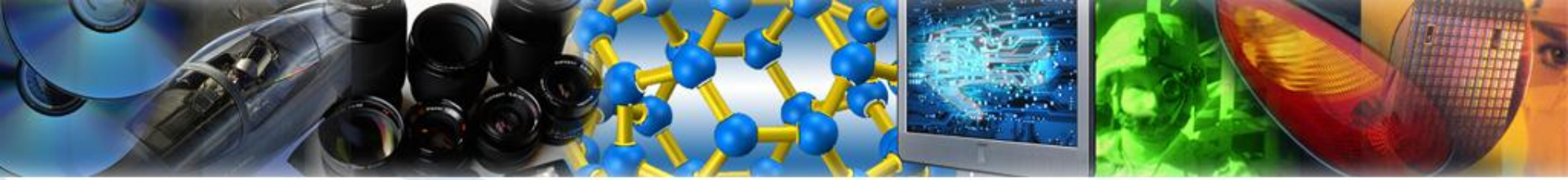
Machining

- Dedicated grinders
- Diamond tooling
- Dust proof enclosures to prevent cross contamination

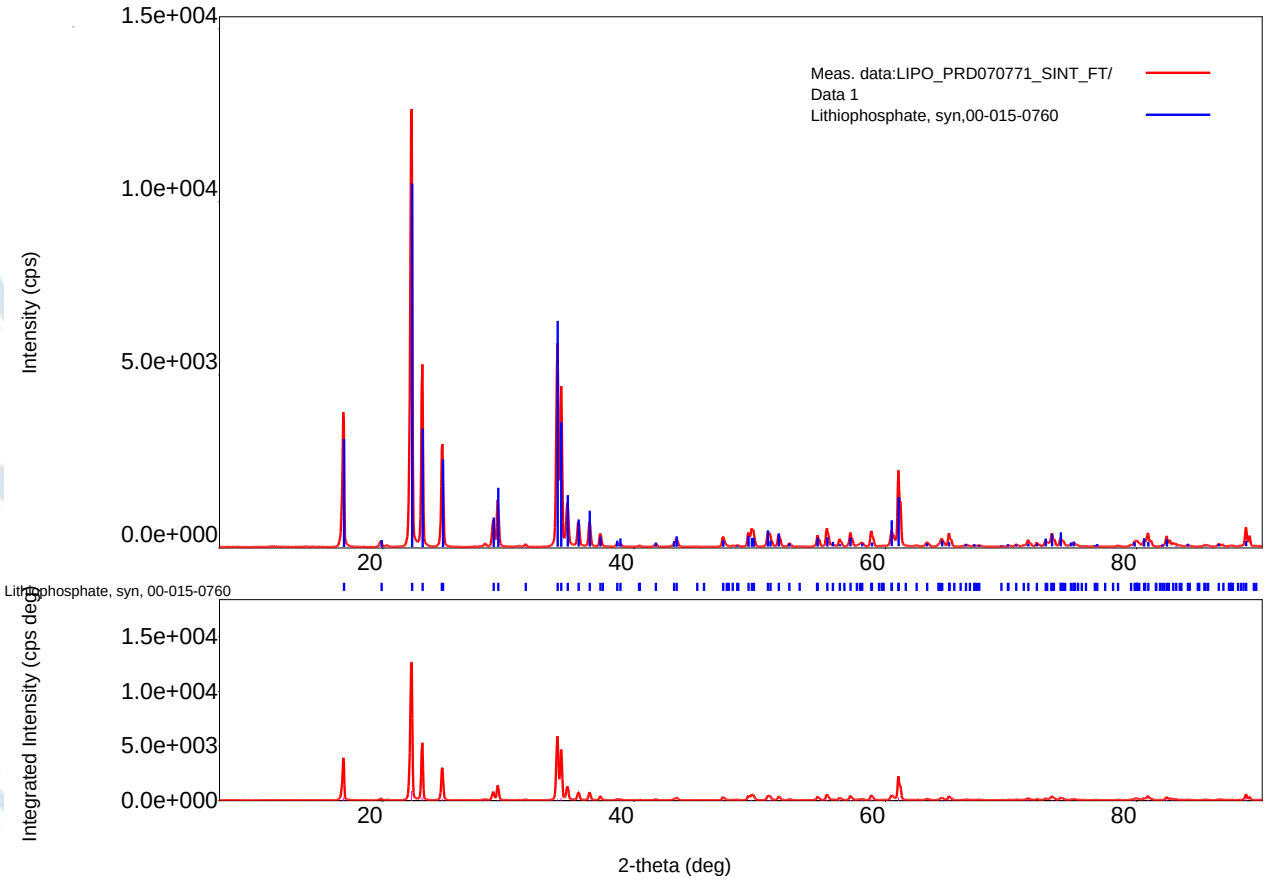


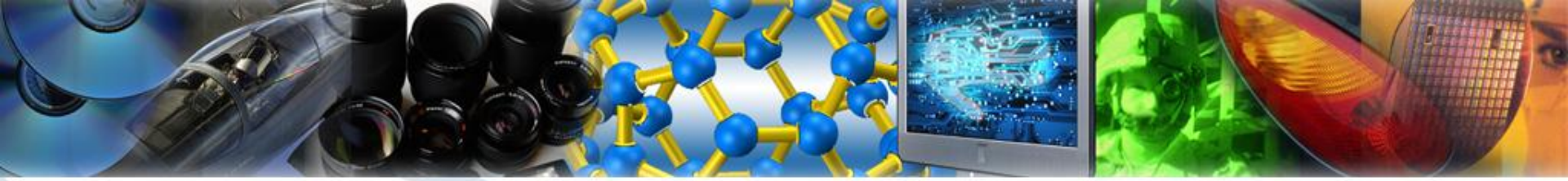
Typical Phase Purity of $LiCoO_2$



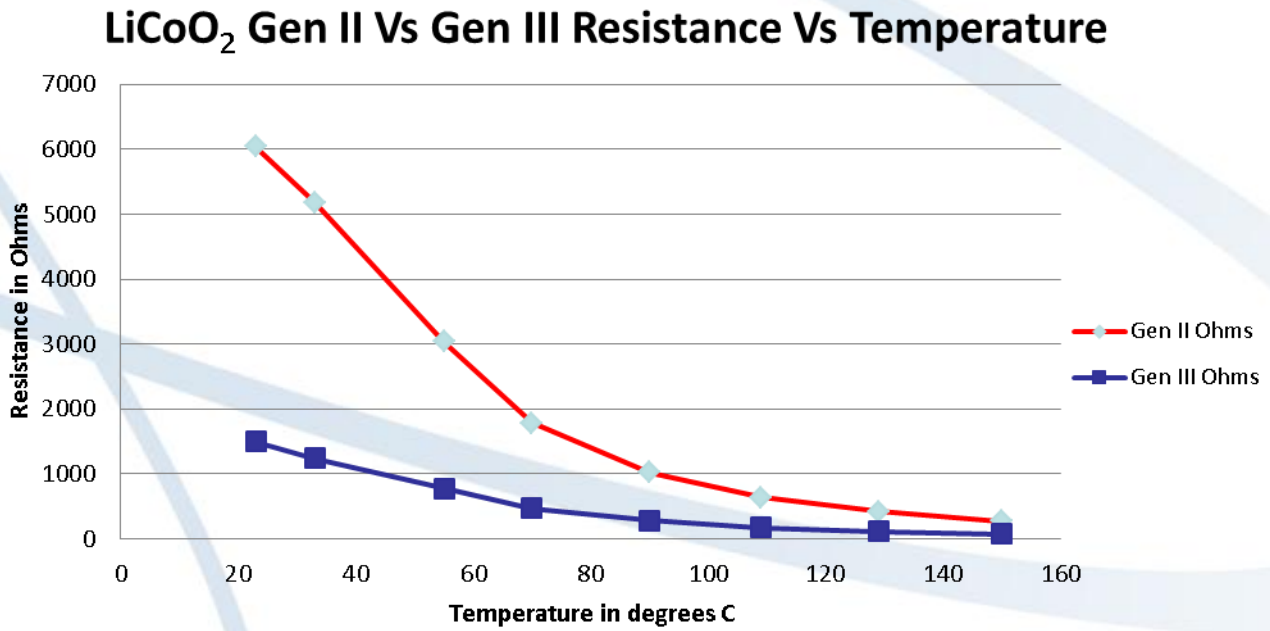


Typical Phase purity of Li_3PO_4

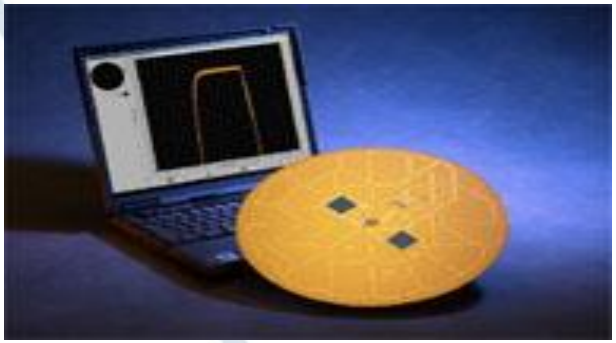




Typical Electrical Resistivity of Sintered $LiCoO_2$ Targets



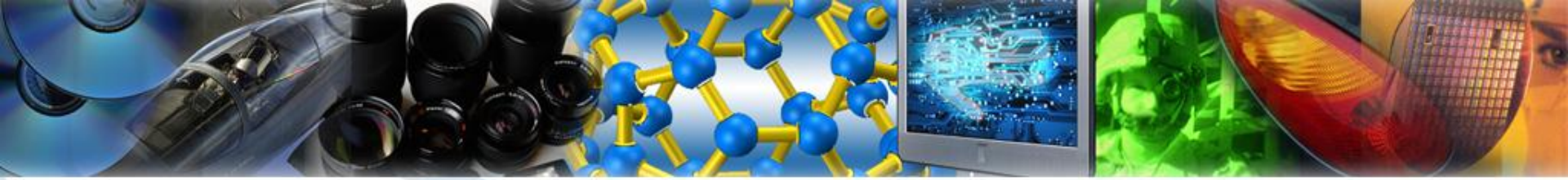
2-point Resistance Using Metal Contacts



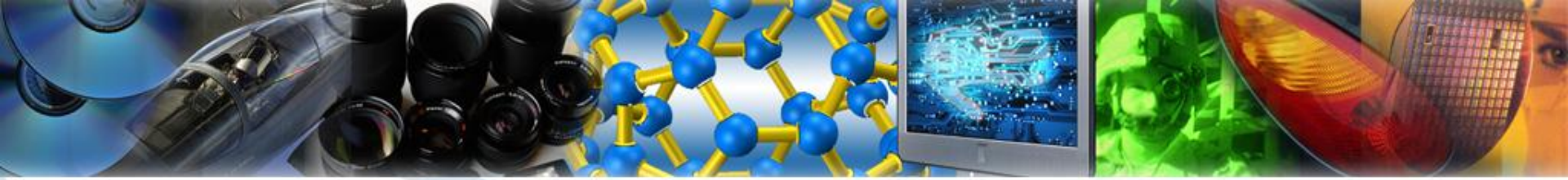
The ORNL-developed Thin-Film Array Slide

Power Paper's Powered Cosmetic Delivery Patch

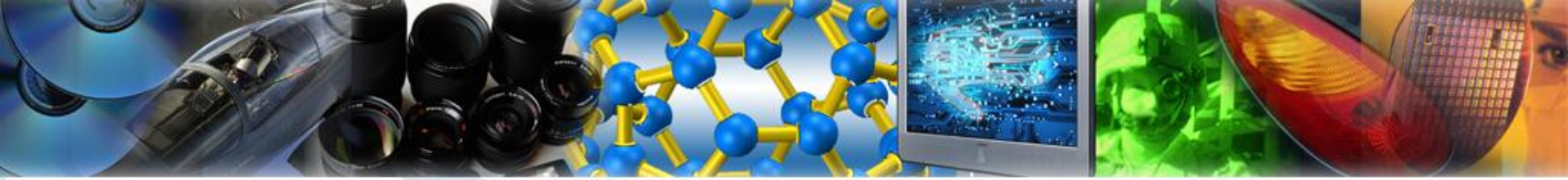
Solicore's Powered Smart Card



- Where is the money Coming from?
  - Applied Materials
  - Bekeart
  - Core-Capital
  - D.E. Shaw Ventures
  - ST Micro
  - Intel
  - DOW
  - In-Q-Tel (CIA)
  - Millennia Materials Fund
  - Texas Instruments

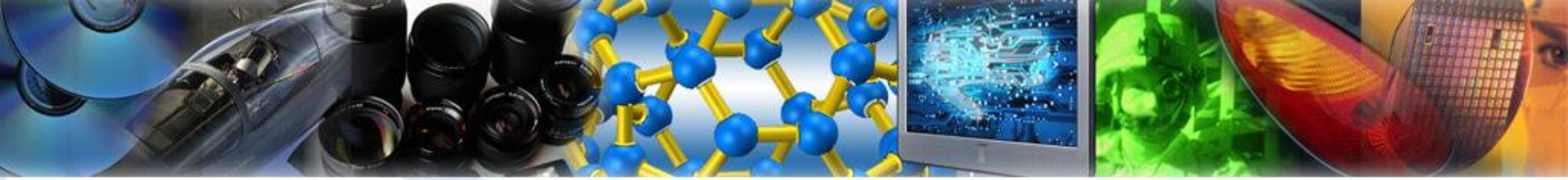


- Design firms qualified for TFB systems integration
  - Advanced Solution Corporation
  - Pacific Design Engineering
  - Synapse Product Development
  - Winland Electronics



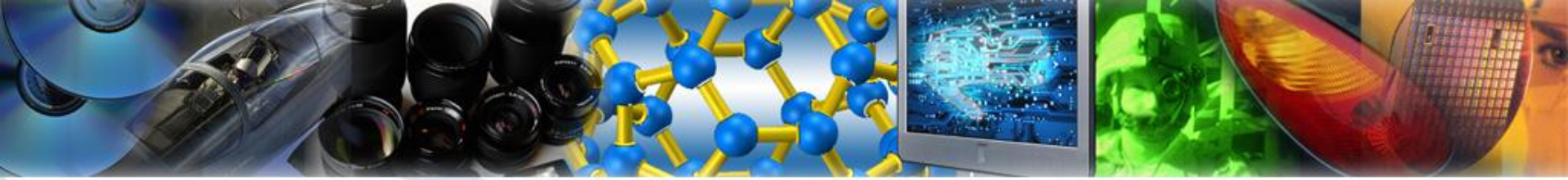
Design awards going to TFB manufacturers

- Infinite Power Solutions
  - VDC Research Group's "BEST IN SHOW" at the Embedded Systems Conference
  - *IDTechEx's* "Best of Sensors Expo" Award
  - INFINERGY™ Micro Power Module (MPM) was the winner of the *IDTechEx Energy Harvesting Award* for Enabling Perpetually Powered Micro-Electronic Devices

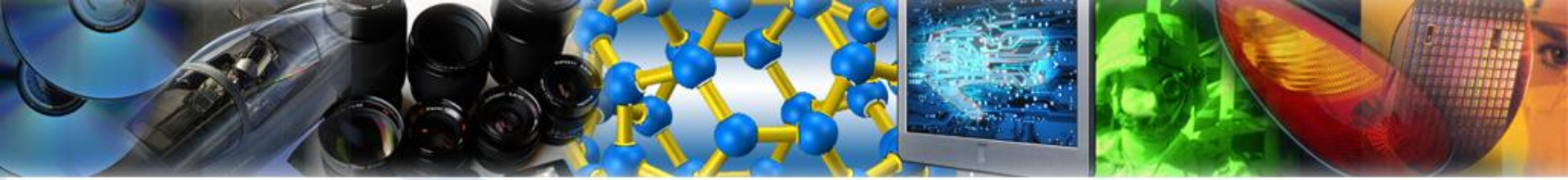


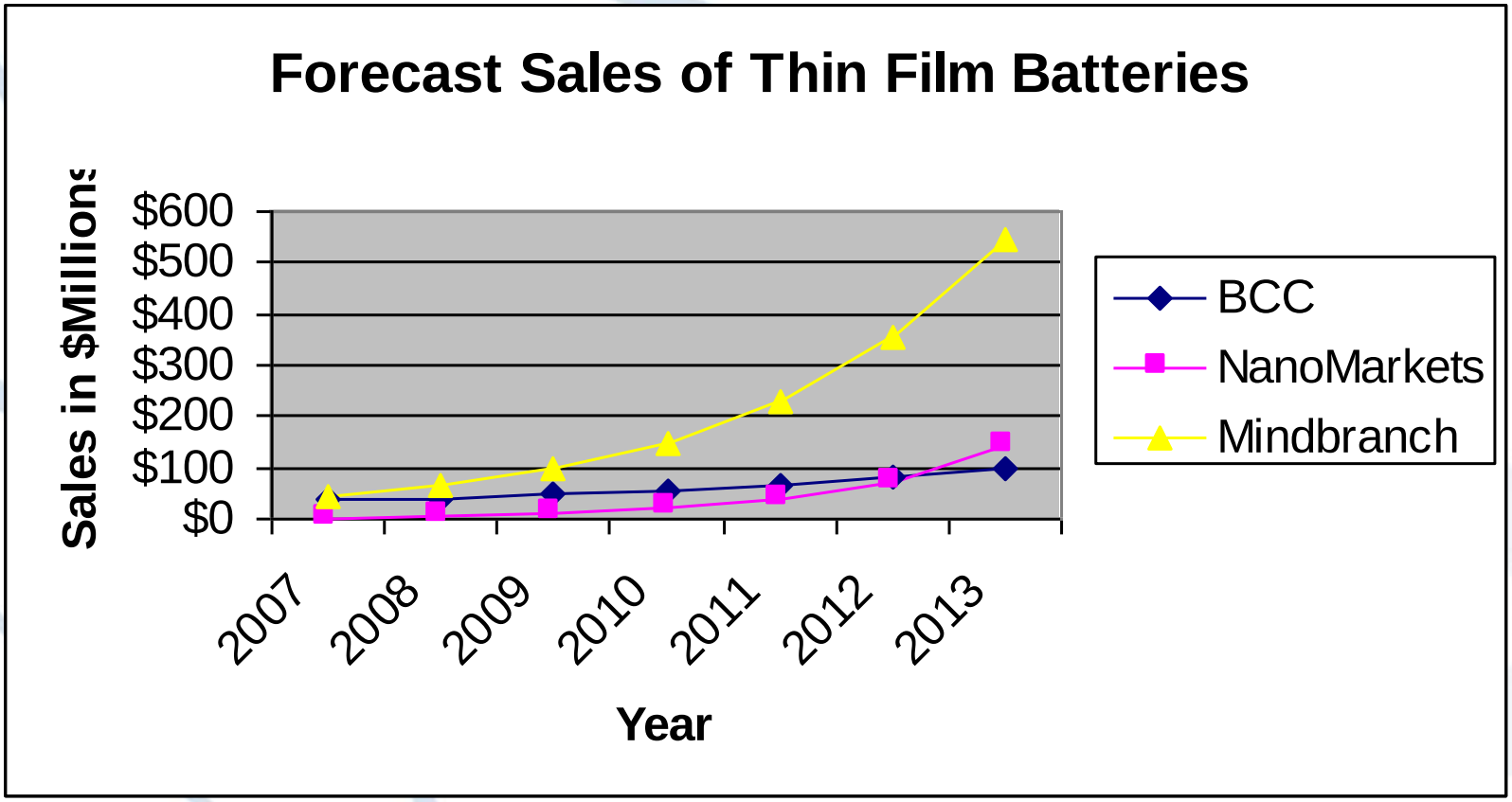
More Kudos

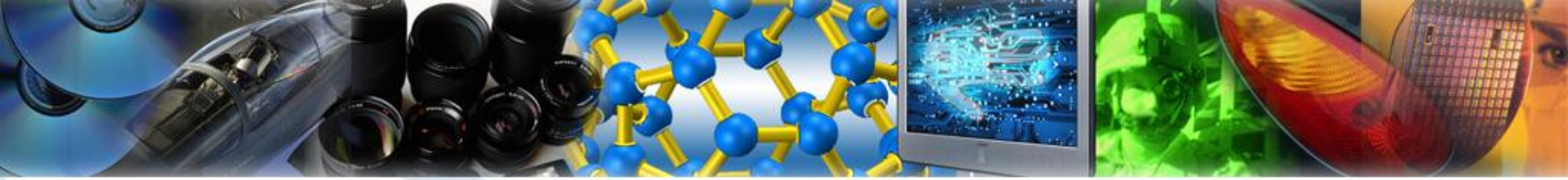
- Cymbet
  - *Sensor Magazine's* "Best of Sensors Expo 2009" bronze award
  - *Frost & Sullivan* Recognizes Cymbet for its Innovative Component-Class Thin-film Batteries for Direct Integration into Electronic Devices and SMT Components



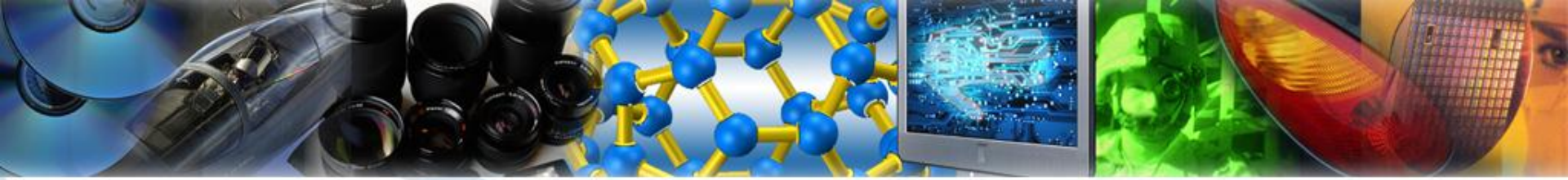
- Retail products available through traditional electronic component suppliers such as:
  - Digi-Key
  - Mouser
  - TI e-store




Forecast Sales of Thin Film Batteries
Sales in $Millions
$600
$500
$400
$300
$200
$100
$0
2007
2008
2009
2010
2011
2012
2013
Year
BCC
NanoMarkets
Mindbranch



- Summary
  - Technology commercialization is a long and brutal process [Bleeding Edge of Technology]
  - (20 years and counting for TFB's)
  - Match of technical attributes with a market opportunity, some charismatic champions with faith (technical risks/costs), and some patient money that loves risk
  - Economic conditions impact the amount of risk loving money available



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