3D lithium ion on chip micro battery for miniature electronic devices.

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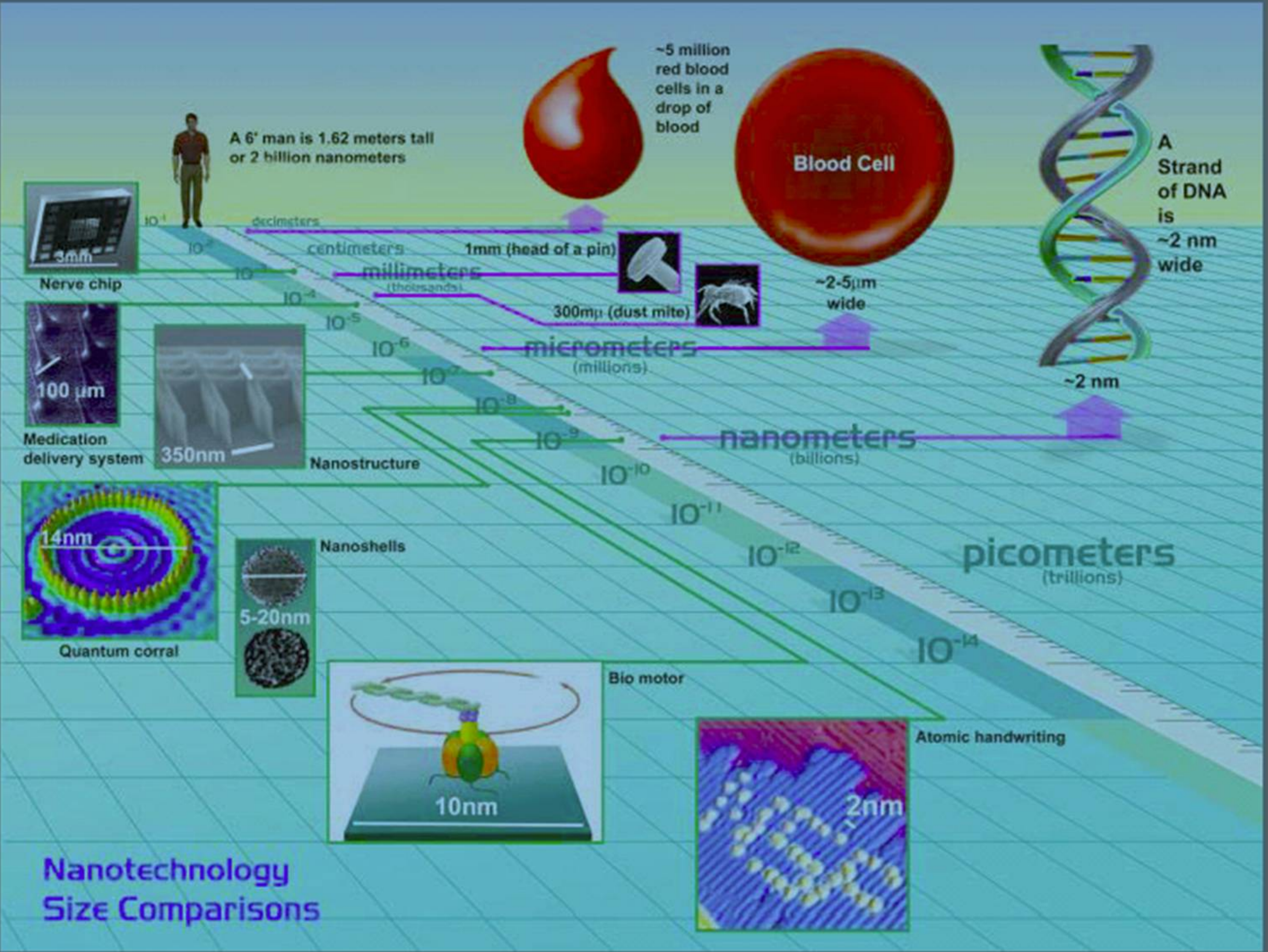


~5 million red blood cells in a drop of blood
A 6' man is 1.62 meters tall or 2 billion nanometers
Blood Cell
A Strand of DNA is ~2 nm wide
decimeters
centimeters
1mm (head of a pin)
millimeters
(thousands)
3mm
Nerve chip
300mµ (dust mite)
~2-5µm wide
micrometers
(millions)
~2 nm
100 µm
Medication delivery system
350nm
Nanostructure
nanometers
(billions)
14nm
Quantum corral
Nanoshells
5-20nm
picometers
(trillions)
Bio motor
10nm
Atomic handwriting
2nm
Nanotechnology Size Comparisons

OUTLINE

The motivation for developing of 3DMBs

Applications of Microbatteries

2D vs.3D design

Interlaced on-Si 3DMBs

Concentric on-Si and glass-3DMBs

Summary

Classification of batteries

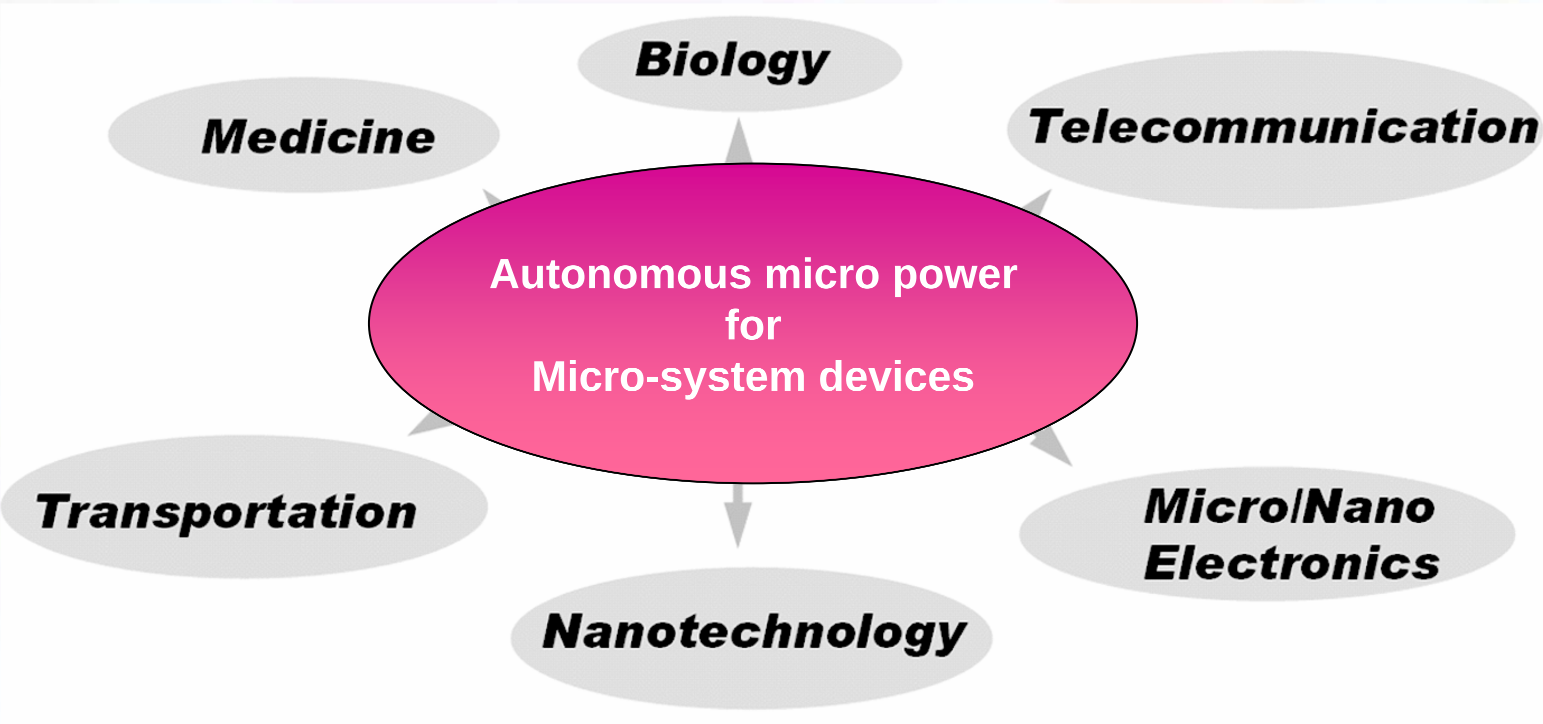
Type	Capacity	Applications
SLI batteries*	50 Ah	Cars, tractors, trucks, electrical vehicles
Portable batteries	2 Ah	Power tools, toy, radio, cellular phones, laptops
Miniature batteries	200 mAh	Watches, calculators, medical devices (pacemakers and hearing aids)
Micro-batteries	**10μAh – 10mAh**	**MEMS, Sensors, CMOS memories, Smart Cards, Smart dust, Drug Delivery systems, Medical implantable devices**

*Starting lighting and ignition

MEMS market forecast

The MEMS industry worldwide reached almost B$ 6 in 2006, and grows with a compound annual growth rate of 14%.

Multidisciplinary; Miniaturization; Mankind needs



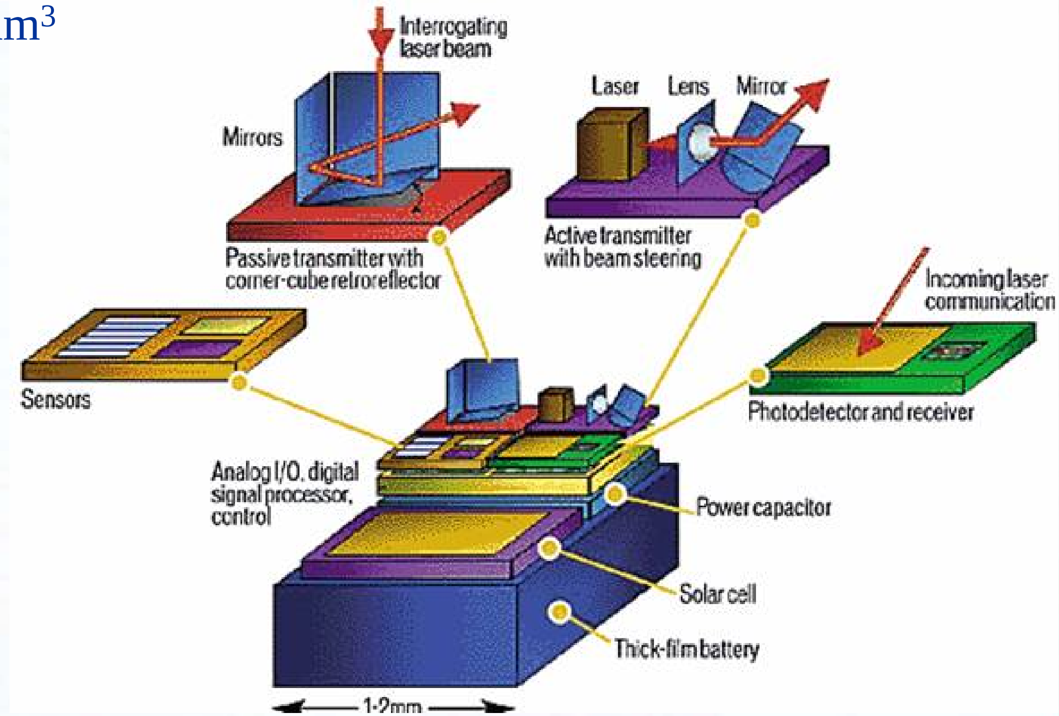
http://media.wiley.com/product_data/excerpt/6X/35273074/352730746X.pdf

“Smart dust” - Future Watch

Energy management is a key component:

Thick film Battery - 0.23mWh/mm^3
Capacitor - 2.3µWh/mm^3

<u>solar cells</u>:
Sun light: 0.23mWh/day/mm^2
Indoors: 0.23- to 2.3µWh/mm^2

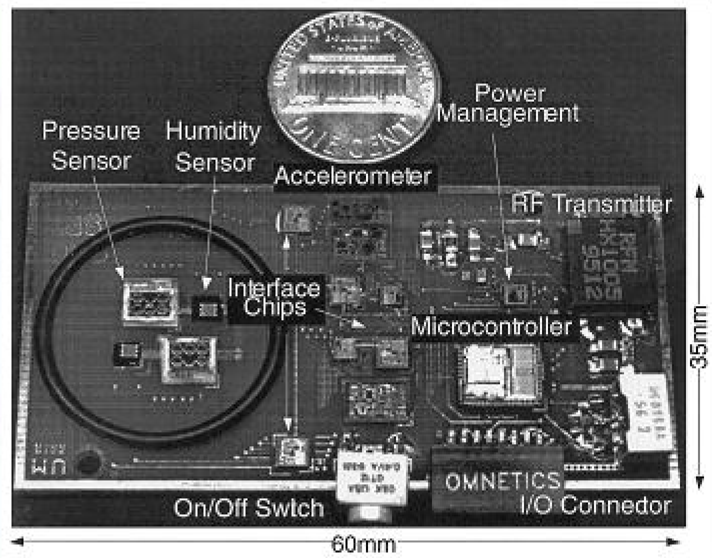


http://www.computerworld.com/mobiletopics/mobile/story/0,10801,79572,00.html

Multisensor microcluster – device size < 1cm^3

multisensor microcluster measures: pressure, temperature, humidity, and vibration/position
Includes: a microcomputer, and has a 50m RF link.

Stand-by power -10µW
peak power - 5mW
pulse duration 10ms
Power supply life-time: months to years



N. Yazdi ea al, Sensors and actuators 84 (2000) 351

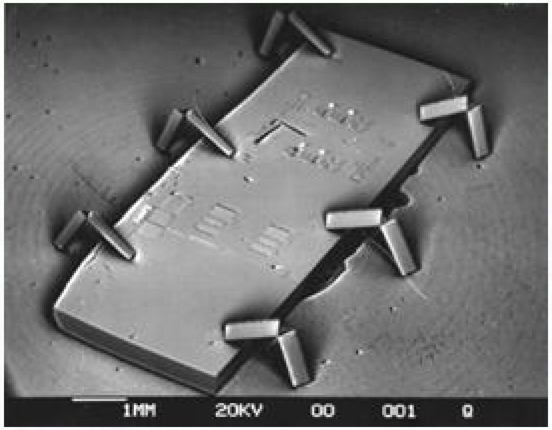
Footprint<0.1cm^2 is suitable for **integrated micro system**

Power density needed to meet 5mW is 50mW/cm^2
Typical thin film lithium ion battery ~0.5mW/cm^2

3DMB meet power density specifications

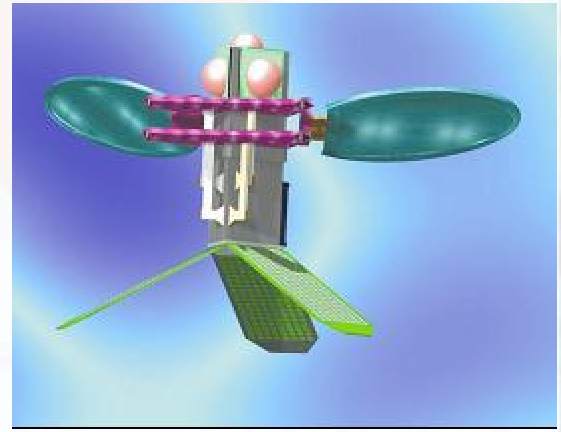
MB for self-sustained hybrid micropower supplies/ J. N. Harb, R. M, LaFollette, R. H. Selfridge, L. L, Howell, J. Power sources 104, (2002), 46

Micro robots



http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=895117

Size<1cm3 (8X3mm2)
Crawling micro robot consumes tens microwatt of power



Legged and winged micro robots will consume total power<10mW provided by on board solar cells

Commercialized smart dust

MICA2DOT available Crossbow tech Ltd;
Applications: Temperature and Environmental Monitoring
Quarter-Sized MICA2DOT(Φ=25mm) ; Battery – 3V coin cell; 7 years battery life

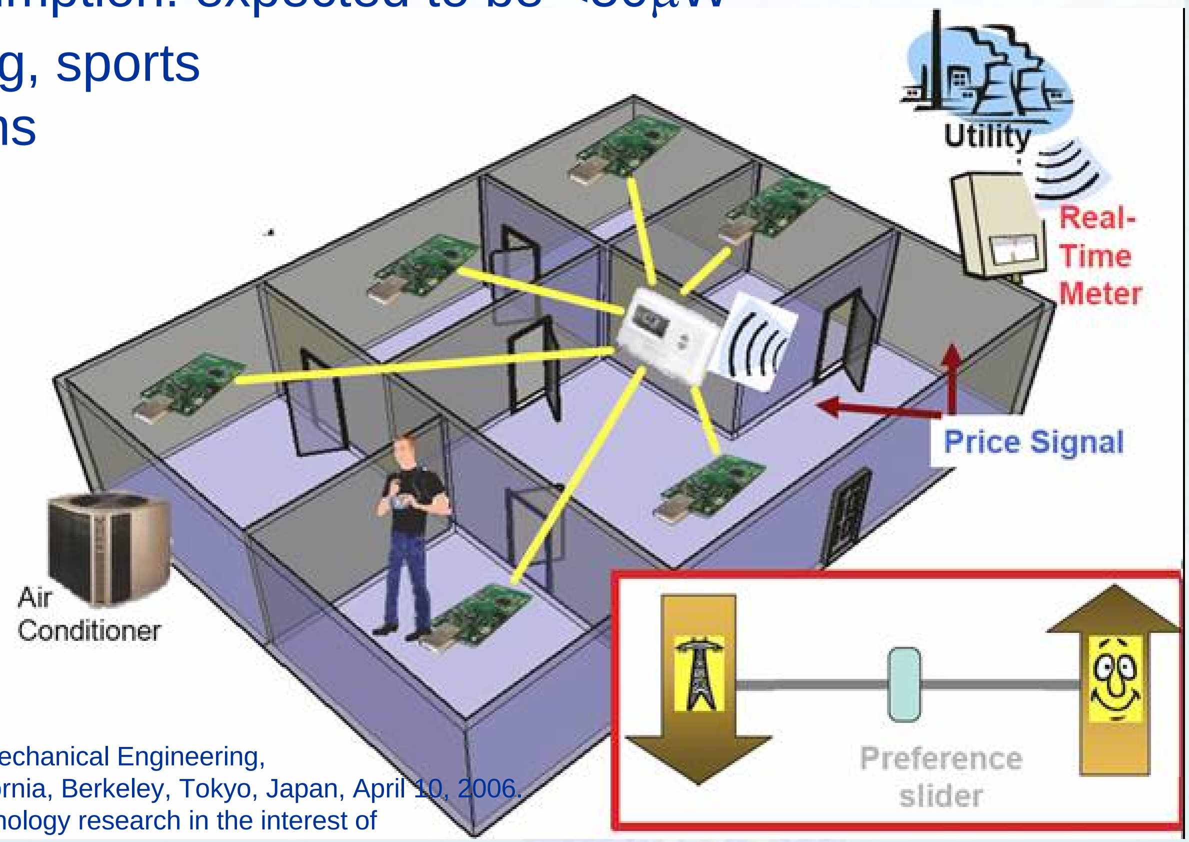
Dust Networks Ltd;
Size – matchbook; Power – 2AA batteries
5 years battery life

http://www.bauer.uh.edu/rfid/Smart%20Dust.pdf

Vision: Small wireless sensors networks are placed everywhere.

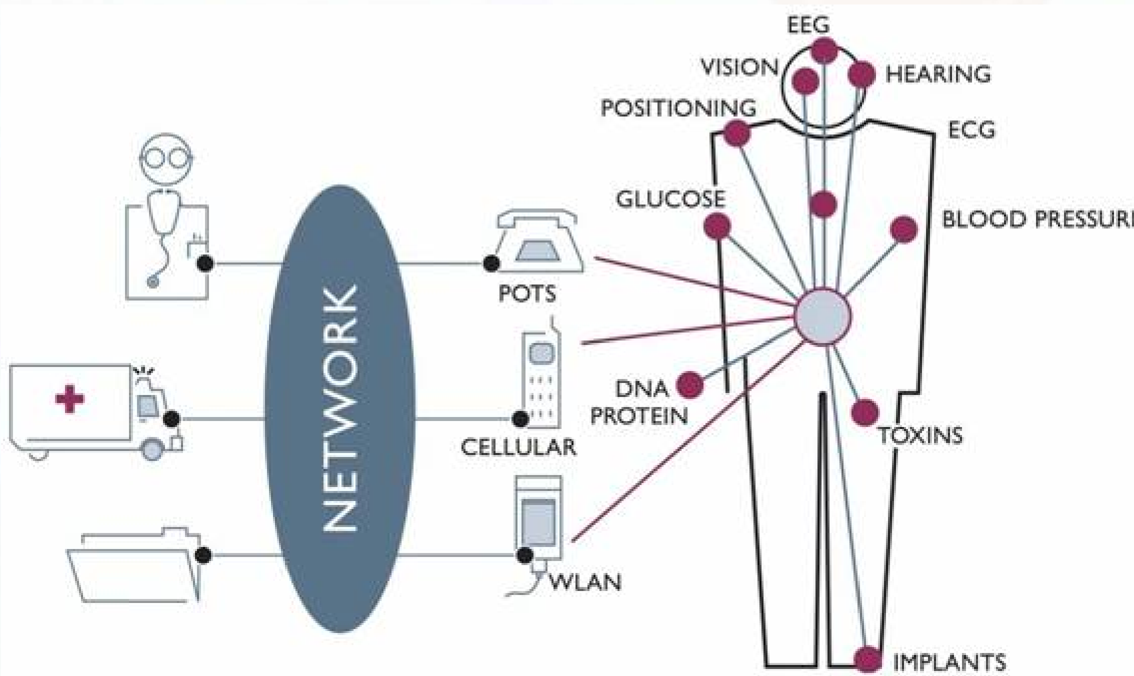
Sensor nodes:self-sustaining,
Average power consumption: expected to be <50μW

Lifestyle assisted living, sports entertainment functions



Prof. Paul Wright, A. Martin Berlin Chair in Mechanical Engineering,
Chief Scientist of CITRIS, University of California, Berkeley, Tokyo, Japan, April 10, 2006.
(CITRIS project –center for information technology research in the interest of

Autonomous Wireless Sensors For Body Area Networks BAN (IMEC Ltd)

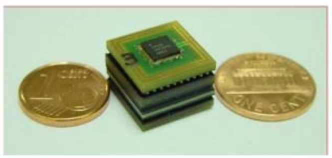


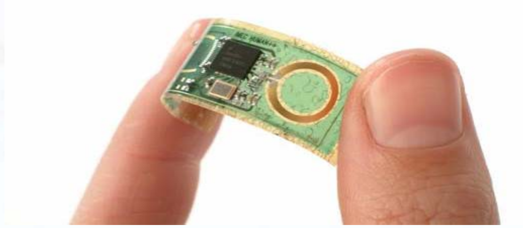
Expertise in: wireless ultralow power communications, packaging, 3D integration technologies, MEMS energy scavenging techniques Lowpower design techniques.

Human++: Autonomous Wireless Sensors for Body Area Networks; Bert Gyselinckx, Chris Van Hoof, Julien Ryckaert, Refet Firat Yazicioglu, Paolo Fiorini, Vladimir Leonov, **IMEC, Kapeldreef 75, B-3000 Leuven, Belgium**

Smart band aid–sensing & communicating with a base station (IMEC Ltd)

Include: 1. radio, 2. micro processor, 3. sensor, 4. power source





1st generation

Power layer-
2 small button cell battery
V6HR NiMH, 2.4V

2nd generation

1cm^3 (3D SIP) approach
Next generation - Thin film Li-ion

http://www.imec.be/wwwinter/mediacenter/en/SR2006/681542.html

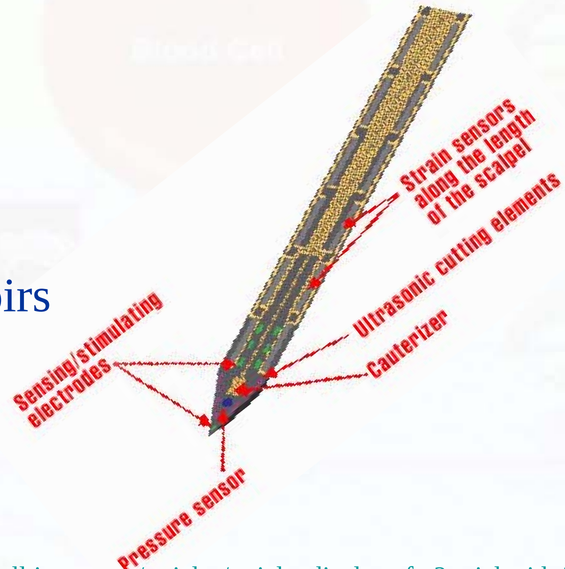
Problem:
Typical capacity < 1mAh → power consumption will have to be reduced
TAU solution:
Improving specification without increasing footprint
complementary approach:
scavengers - can recharge the battery continuously

Scientific report, 2006

Wireless sensor module as miniaturized but conventionally-connectorized (left) or as integrated 1cm3 volume 3D stack (right).

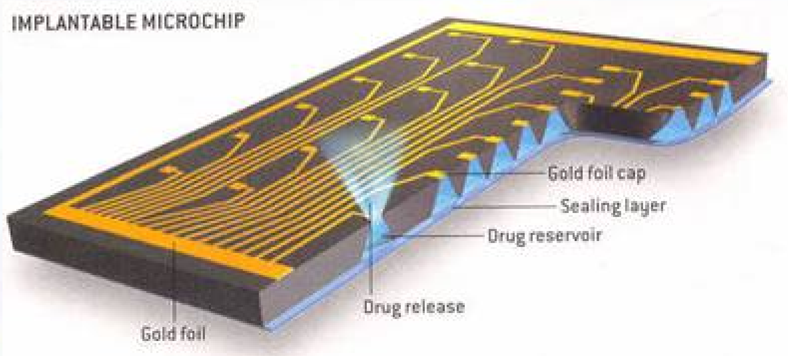
NOVEL MEMS & MBs for CLINICAL NEEDS:

- surgical tools; implantable e-devices;
- sensors and monitors for physiological parameters;
- neurostimulators; devices for pain relief;
- control over drug delivery from implantable reservoirs



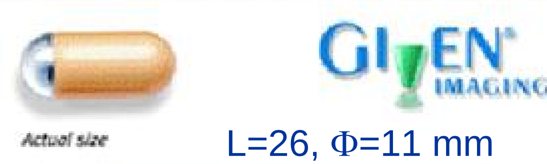
http://www.smalltimes.com/articles/article_display.cfm?article_id=268501

The "Data Knife" Pittsburgh, Verimetra Inc.



Companies: ChipRx, MicroCHIPS Inc.

Neuro-modulator



L=26, Φ=11 mm

http://www.batteriesdigest.com/gastro.htm

TAU 3DMB – The Answer To Sub –mm^3 battery

	Dimensions	Energy density Wh/L	Power density W/L	Charge rate
Varta 65011	d=4.7mm h=1.4mm V=0.02ml	124	62	0.5C
Great batch Ltd (medical applic.)	V=0.7ml	185	925	5C
3DMB*	**Tailored to application (foot print, design, performance)**	**306**	**2550**	**8C**

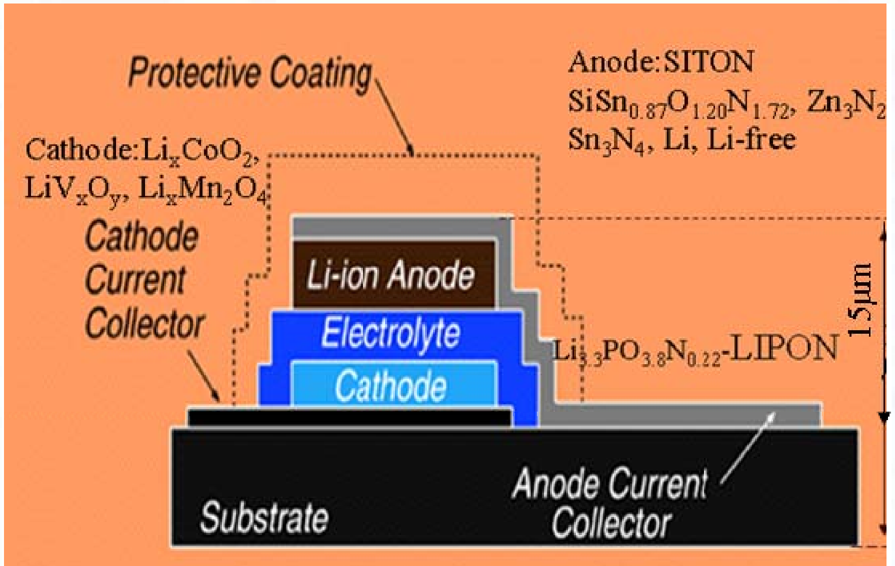
*after improvement of current collectors

MB requirements for MEMS applications:

- High integrity containment & minimum size
- Long-term Energy Supply in MEMS need High Power Level
- Rechargeability
- Minimal internal resistance, **SAFETY**,
- Produceability in large quantity and low cost

Fundamental problem of 2D-MBs: limited active electrode surface area

Thin-film batteries
The most advanced of LiBat systems



J.B. Bates et al (at Oak Ridge National Laboratory) SSI *135 (2000) 33*

	Typical performance	**TAU**
Voltage [V]	2-4	**1.7-3**
Capacity [μAh/mm^2]	1-3	**100**
Energy [μWh/mm^2]	2.5-10	**170**
Power [μW/mm^2]	4 - 70	**20 (500*)**

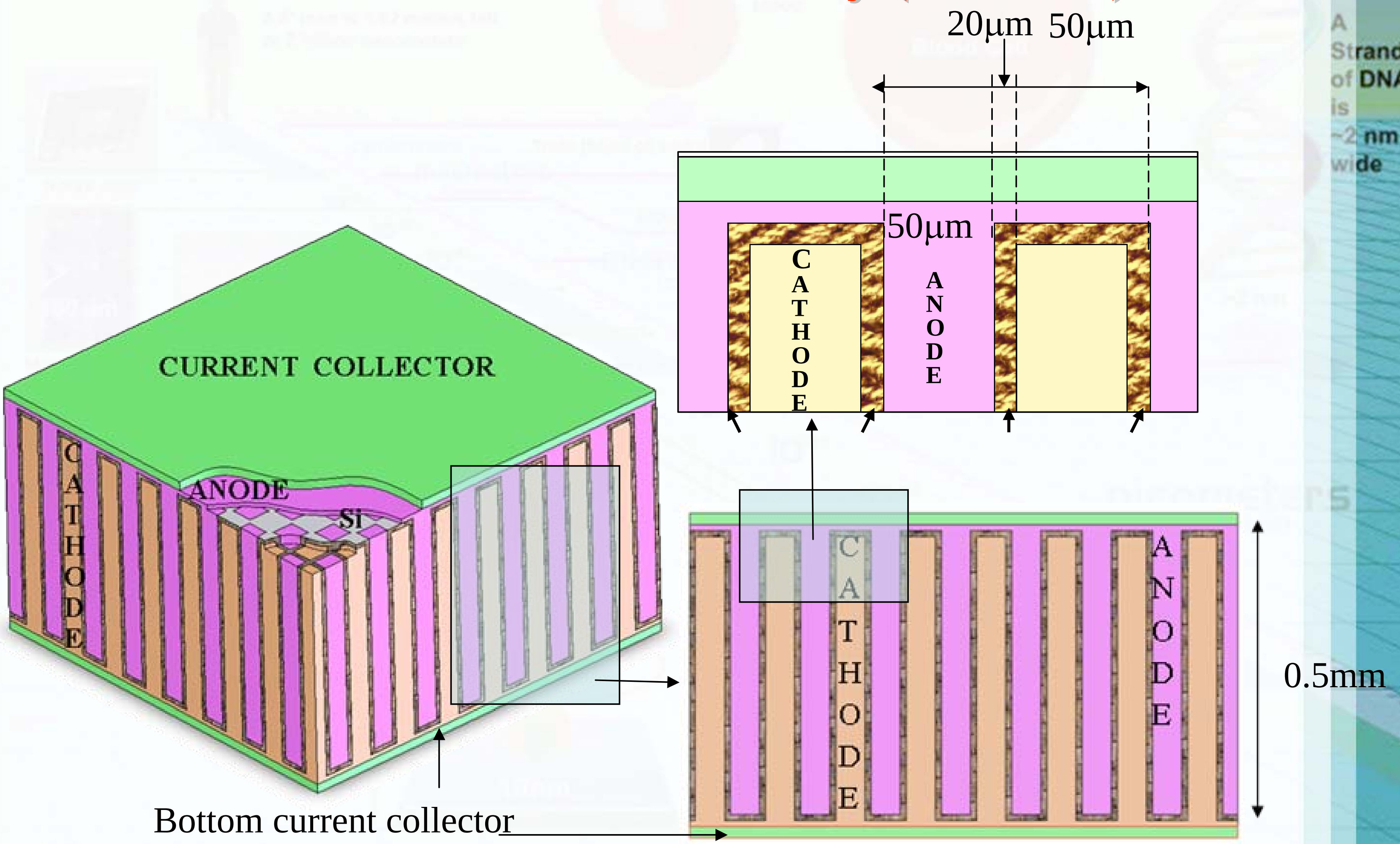
* future value

U.S companies have silences the Thin-film MB ORNL tech:

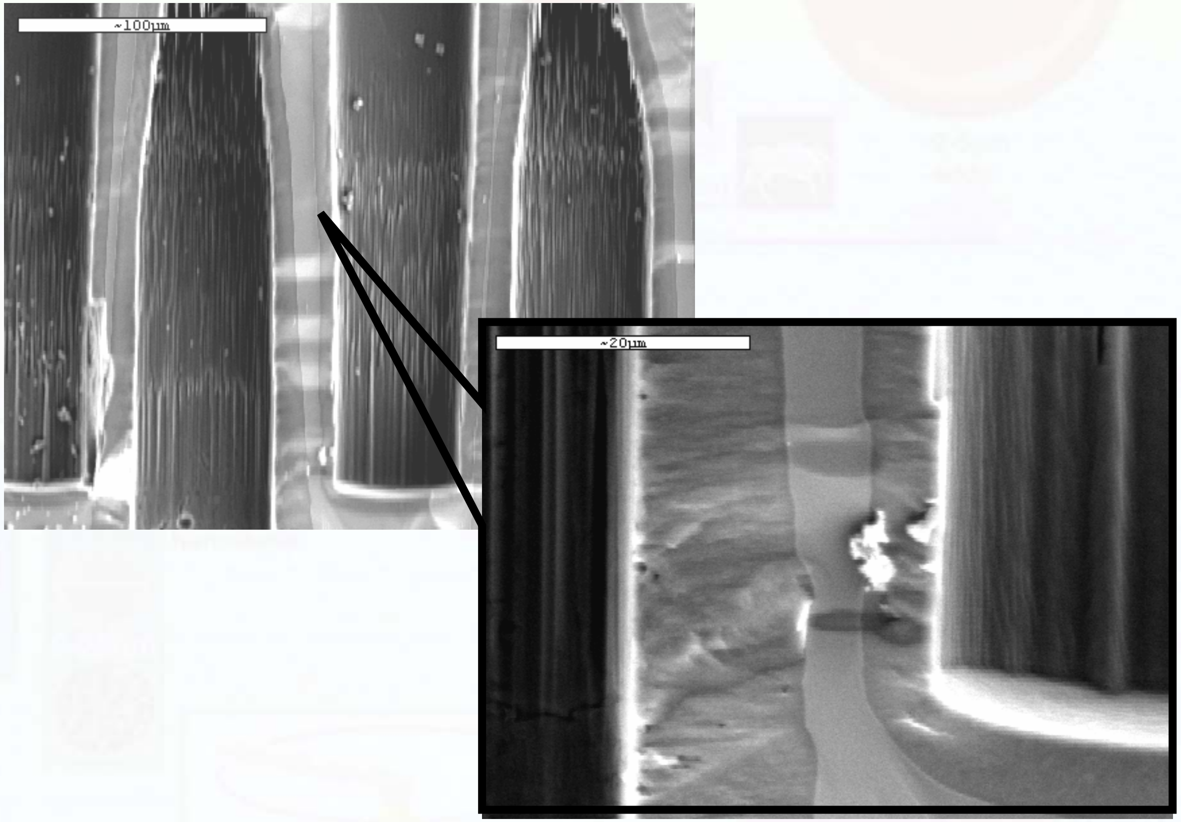
Bordeaux Univ.& Hydromech.(HEF)1,
Eveready Battery Co.1
Front edge technology inc.,
LiTE Star

Oakridge Lab.2,
Cymbet inc.,
Excellatron solid state Inc.

3D-Interlaced Microbattery (3D-IMB)

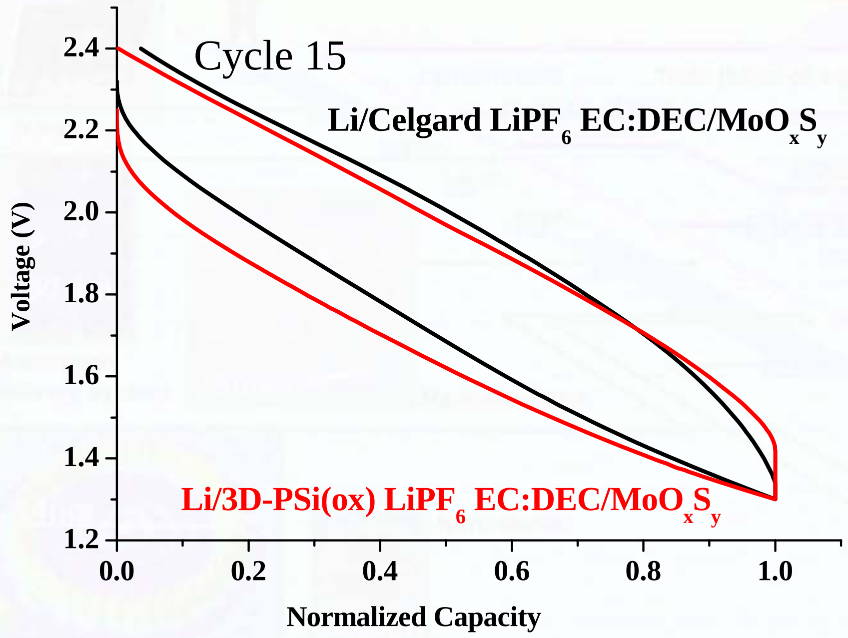


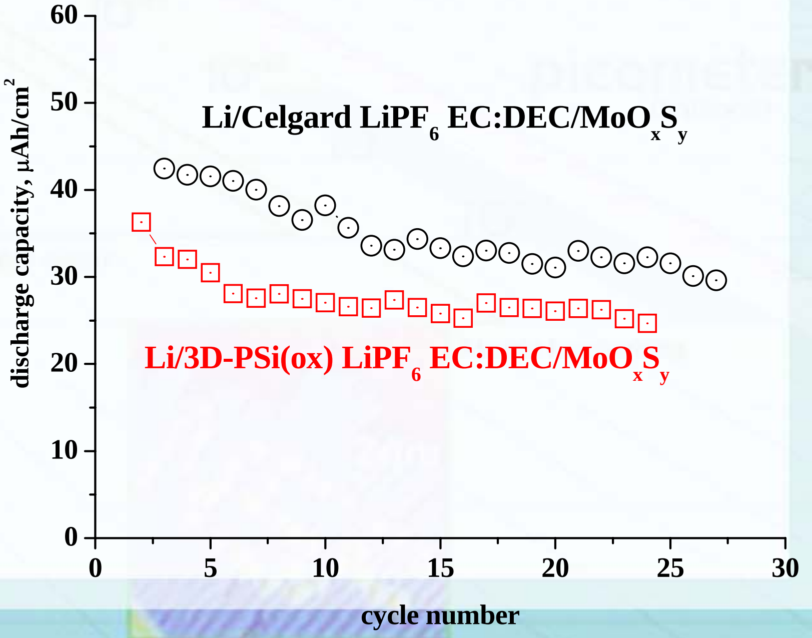
SEM image of porous Si partition



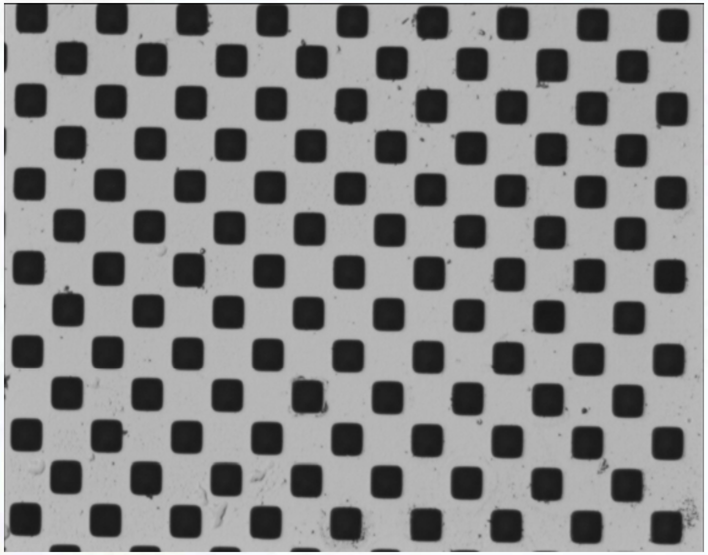
A Strand of DNA is ~2 nm wide

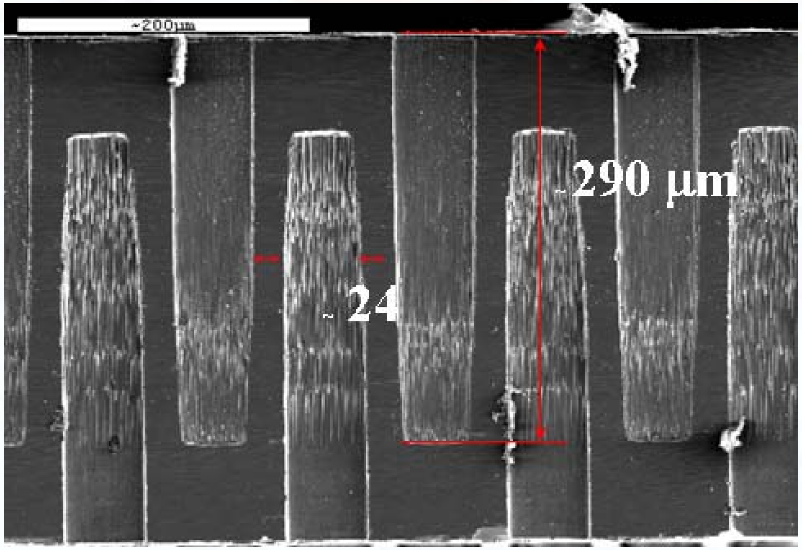
Cycle life of thin-film Li/MoO_xS_y cells with 3D interlaced porous Si

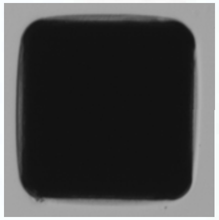


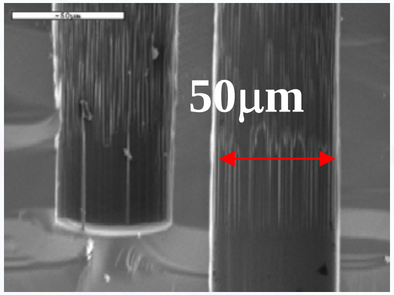


Optical and SEM images of the interlaced Si formed by double-side DRIE (*deep reactive ion etching*)







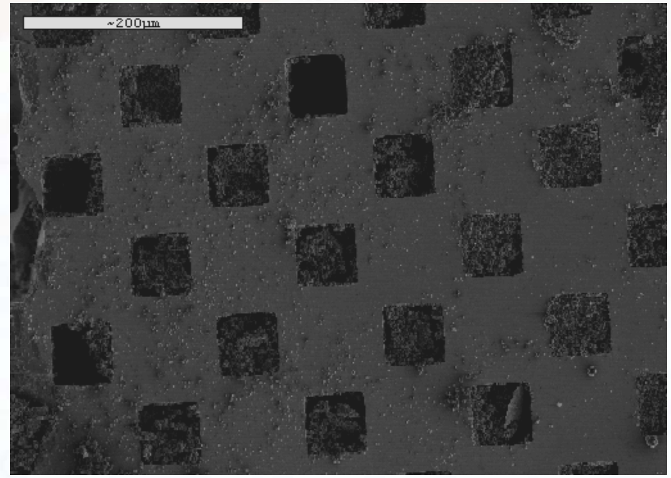


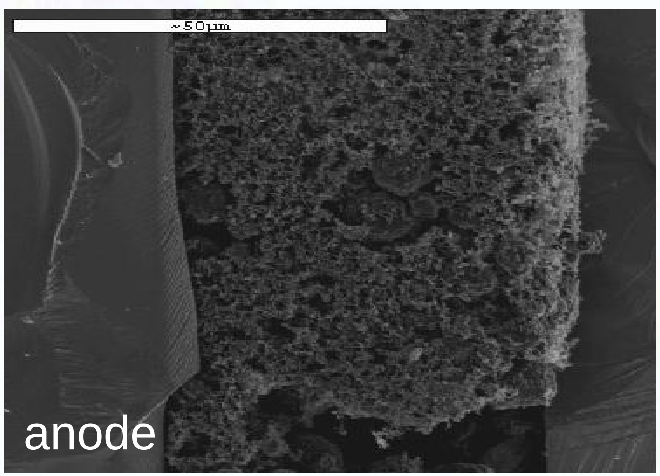
A Strand of DNA is ~2 nm wide

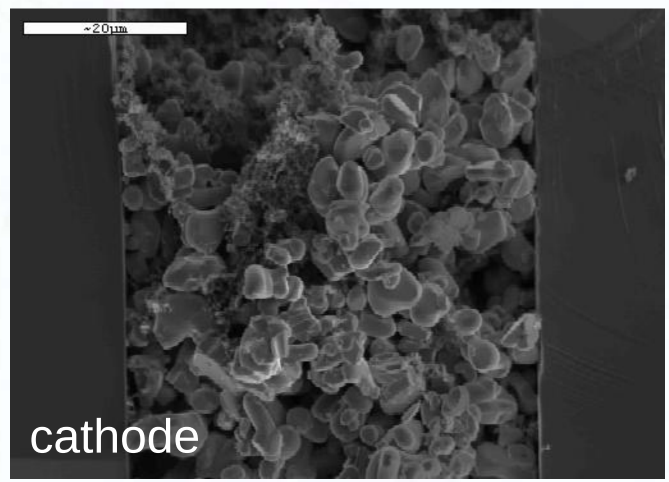
Si microcontainers filled by anode and $LiCoO_2$ cathode

Anode composition:

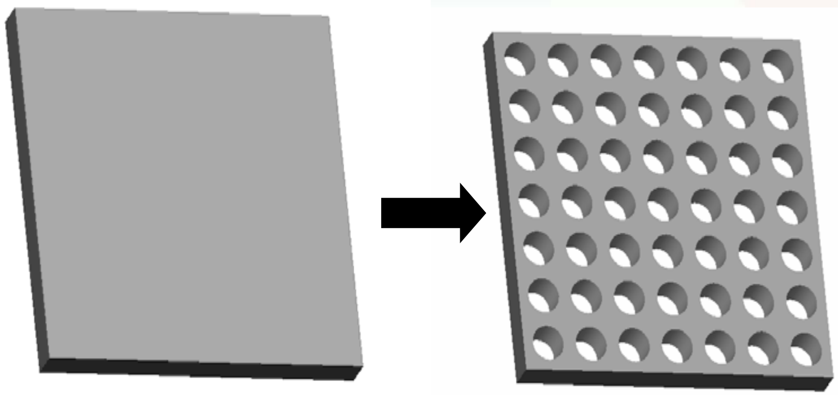
MCMB (Meso-Carbon Micro Beads) 6-10µm
SB - Shawinigan Black
Binder

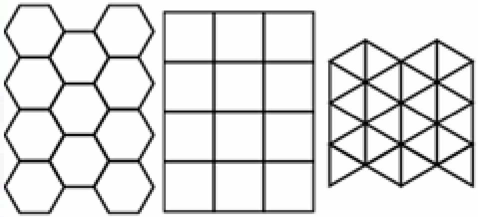




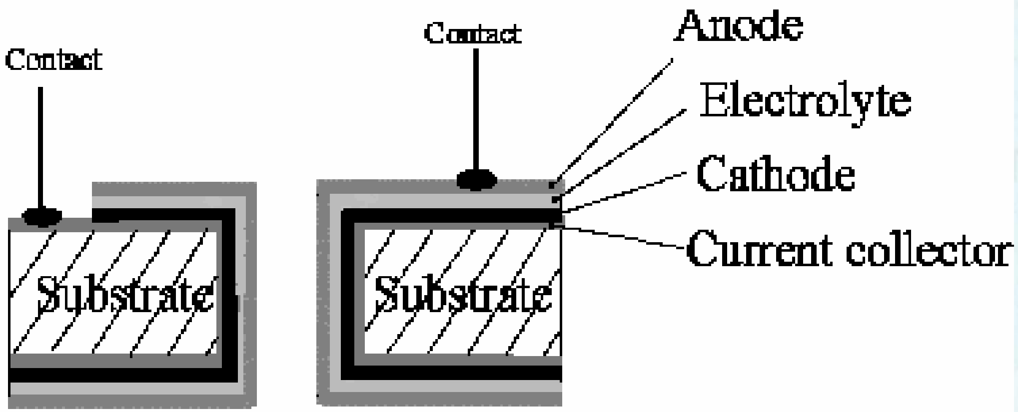


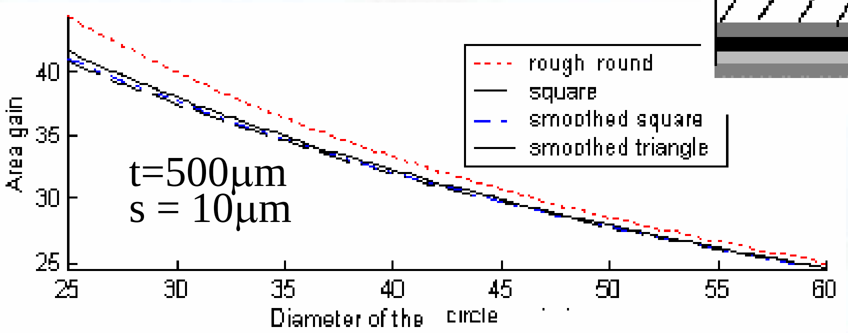
STRATEGY: Max PD&ED within the footprint area





t = 450 μ m
d = 40 μ m
s = 10 μ m,
Area Gain (AG)=23





$$A.G. = \frac{\pi d}{(d+s)^2}\left(t - \frac{d}{2}\right) + 2$$

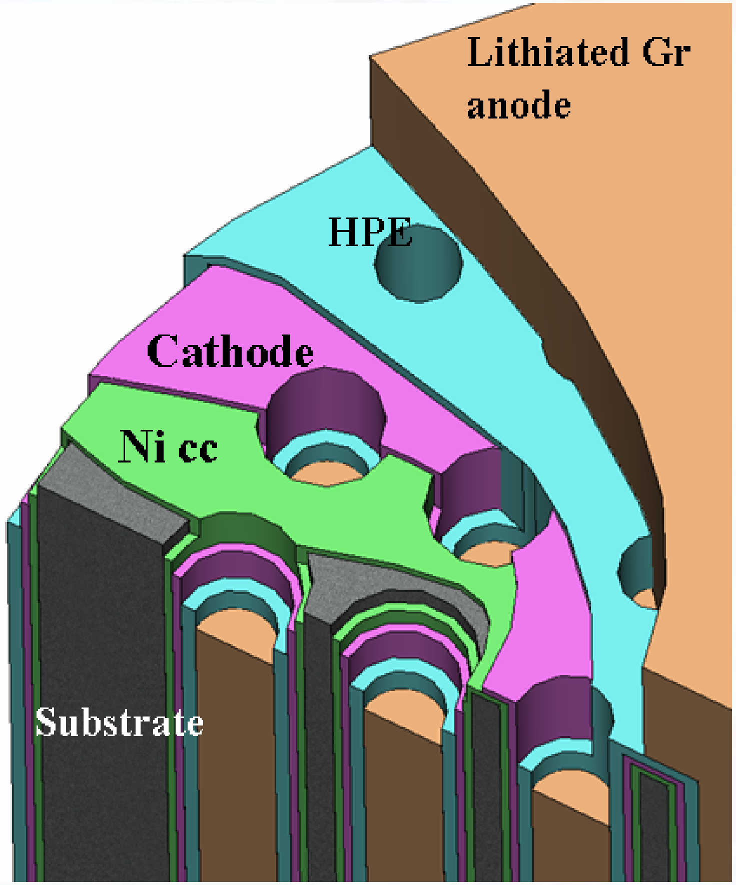
3D-Concentric MB on perforated substrate

Substrates:

Perforated silicon prepared by ICP-Bosch process

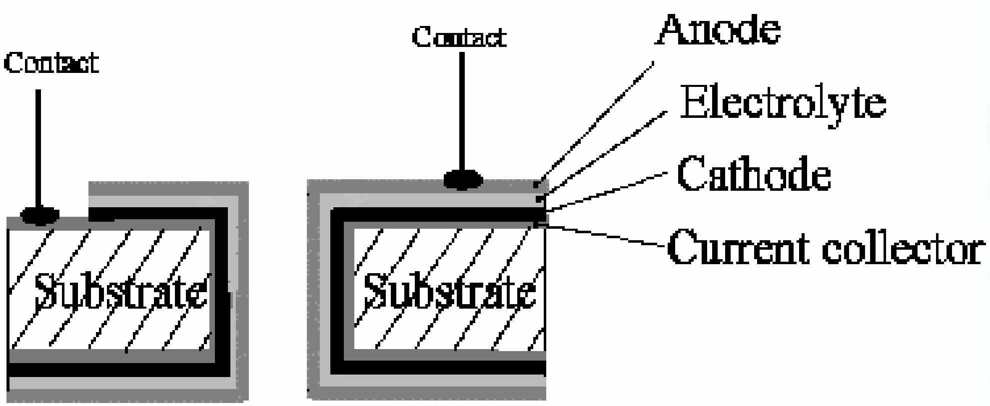
Glass capillary arrays

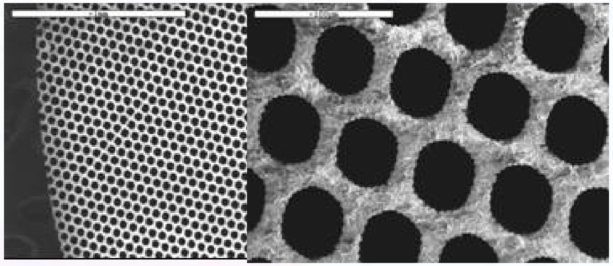
Photosensitive glass (Foturan)



3D-MB sequential fabrication stages

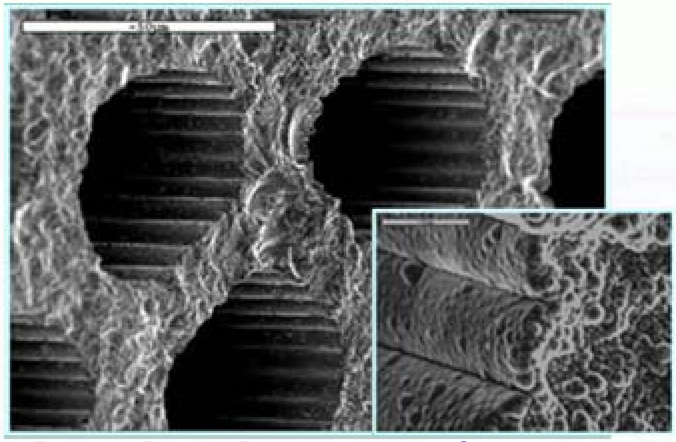
1. Surface pretreatment of substrate sidewalls.
2. Electroless deposition of a current collector.
3. Electrodeposition of a thin-film molybdenum sulfide cathode.
4. Hybrid-polymer electrolyte (HPE) membrane coating.
5. Filling of the remain volume of holes by graphite based anode
6. Mounting of lithium foil at the top of the conformally coated perforated substrate.
7. Charging of the cell with liquid electrolyte and packing
8. Testing and Characterization (XPS, TOF SIMS, XRD, SEM, AIC)



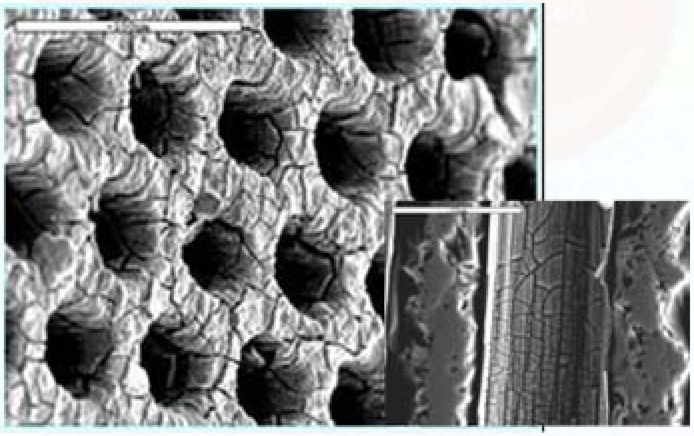


Muli-chanel plates- glass substrate

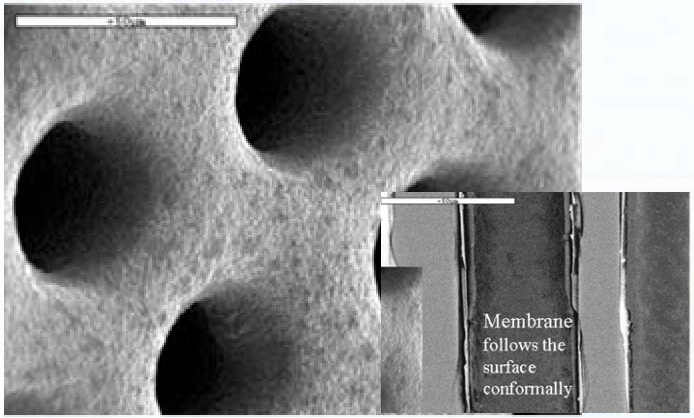
Feasibility of 3D concentric microbattery fabrication



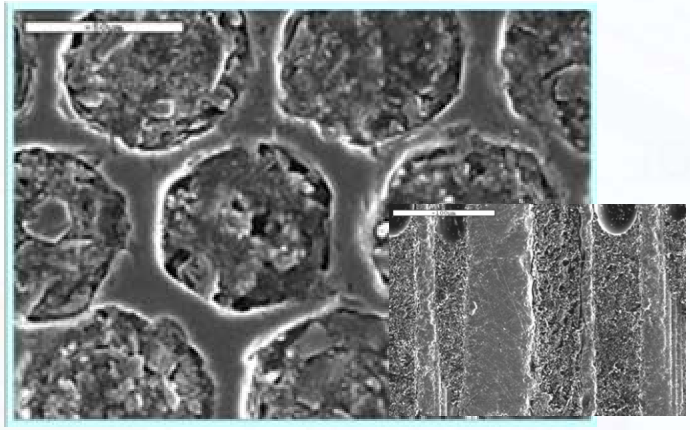
Electroless depostion of Ni current collector



Electrodeposited Cathode

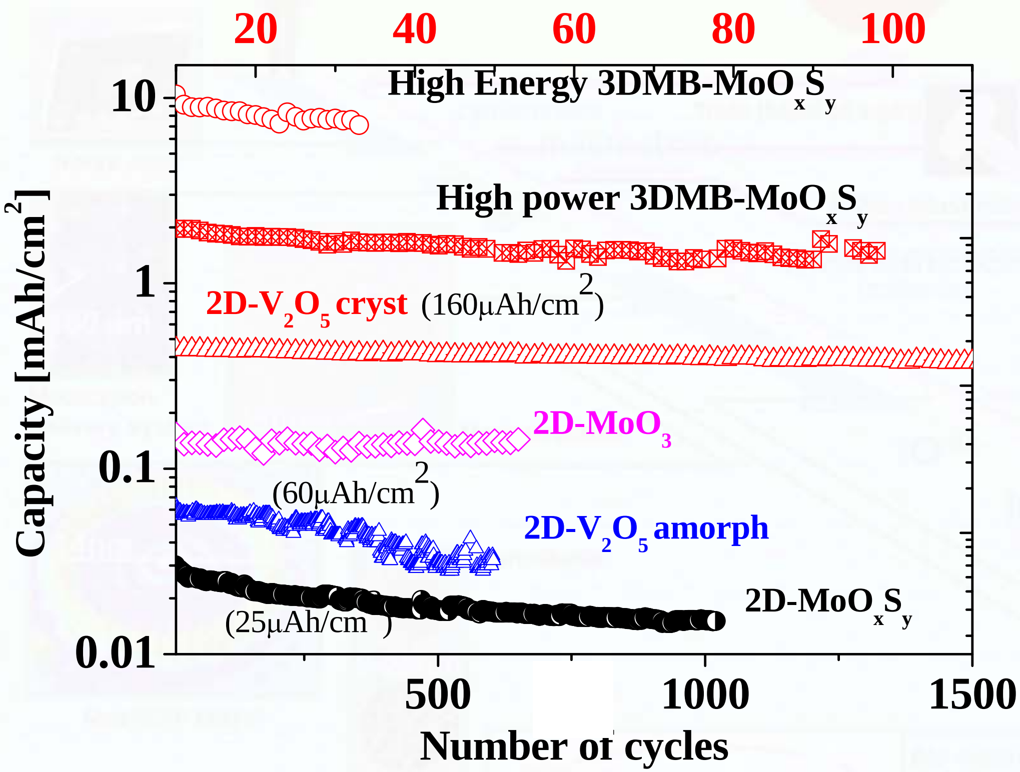


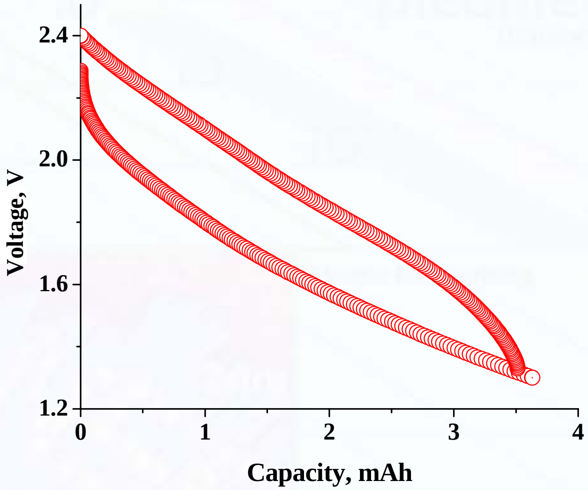
Conformal Membrane coating



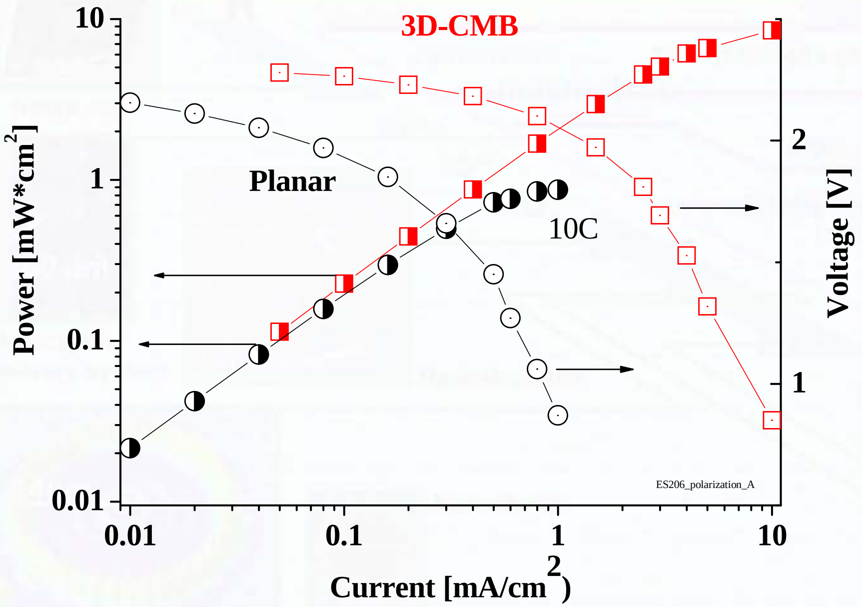
Filled Graphite anode

Cycle life of planar and 3D-CMBs

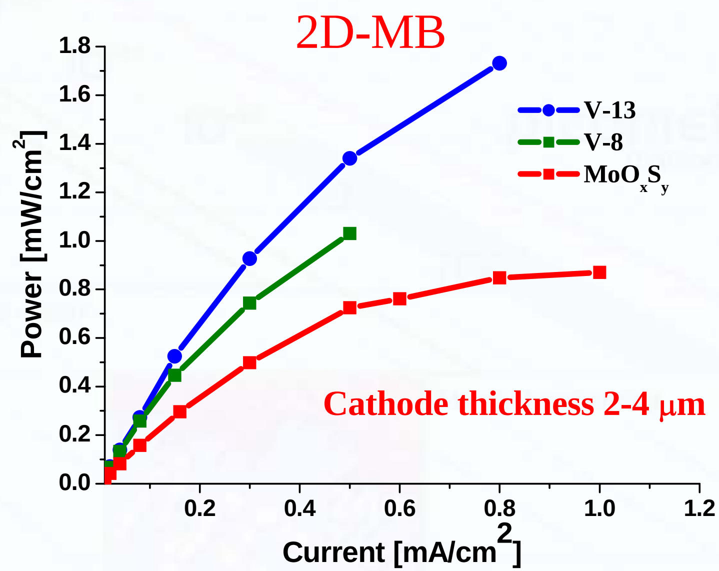




Polarization curve



τ_{pulse}=2min



TAU 3D-MB present and predicted performance

	Operating Voltage [V]	Capacity [$\mu Ah/mm^2$]	Energy [$\mu Wh/mm^2$]	Power [$\mu W/mm^2$]
Present High-energy configuration	1.7	100	170	~20* 200**
Future TAU High-power configuration	3	40	120	~500
After improvement of current collectors	3	60	180	1500
Typical performance of 2D Li thin film Battery	*2-4*	*1-3*	*2.5-10*	*4-70*

* Continuous operation
** polarization pulse
AVG density of battery is 2.5gr/ml

Safety of High Power Lithium Ion Batteries

High power lithium ion batteries can supply 15C of current.
However they are not safe enough
(see for example 120 fire / explosion incidents reported in;
http://www.rcgroups.com/forums/showthread.php?t=209187

Causes:
Overcharge; Internal or external short-circuit;
Mechanical impact (abuse); External heat (abuse) etc.

3DMB battery consists of ~30,000 holes/cm^2.
In each one there is a complete lithium ion micro-cell.
All these “micro-cells” are connected in parallel.

It is projected that such as multi-cell battery will be safer
than the traditional ones as there is a 10-20 micron insulating wall
(coated by 2 micron nickel film on both sides) between neighboring micro-cells
(surrounding each one of them).

Summary

1. A technology for the manufacturing of 3DMB based on the interlaced Si has been developed, complete cells to be tested soon

2. The 3D-CMBs with modified MoO_yS_z cathode exhibited stable cycle life with about 100 $\mu Ah/mm^2$ reversible capacity, ~100 times higher than that of a planar 2D thin-film cell of the same footprint with non-modified cathode.

3. The 3D-CMBs with electrodeposited V_2O_5 are under testing

4. High-power 3DMBs on perforated substrates are expected to be safer than the ordinary batteries