Paving the way towards solid-state 3D thin-film Li-ion batteries

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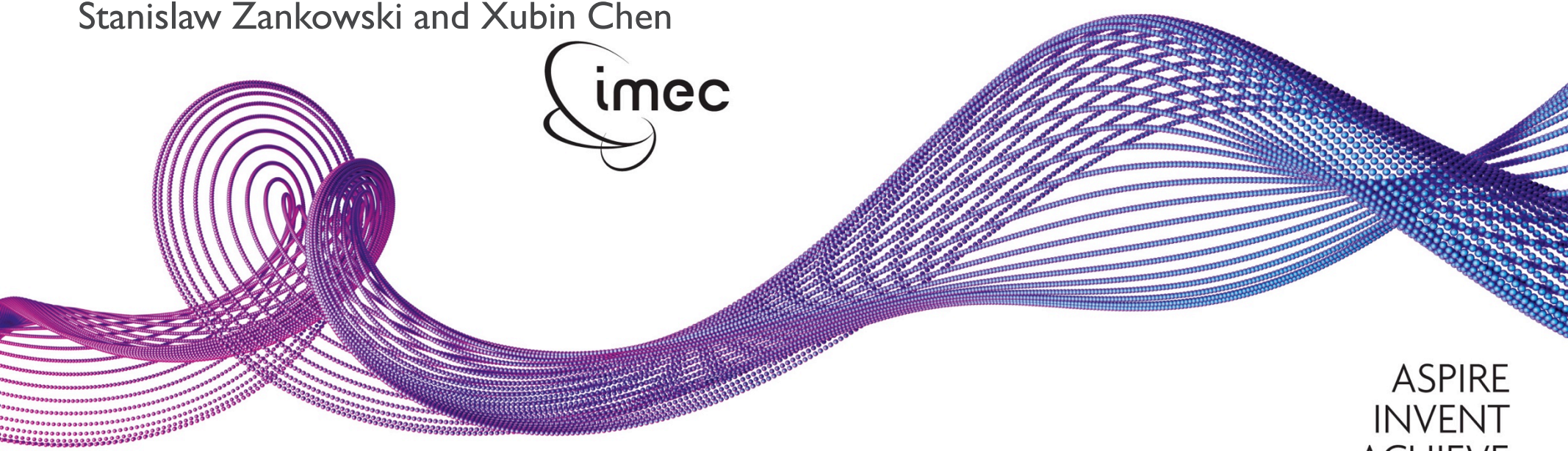

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THE BATTERY IS THE LIMITING FACTOR IN TECHNOLOGY

The emergence of Li-ion battery has enabled new applications which emerged and evolved over the last decade...

High Energy density of Li-ion = portable energy source can be made small enough

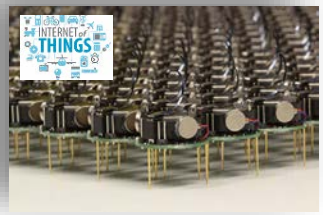
Portable electronics

Automotive

Storage

And will continue to do so for future electronics.

Form factor, Safety, and Fast charging are needed for future developments



IoT

Wearables

Health

Flexible electronics

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APPLICATION SPECTRUM IS WIDENING

Rechargeable Li-ion batteries

Power on board

Back-up power chip or PCB

Portable electronics

Hobby and power tools

Vehicles

Bikes, automotive, aviation, rail,...

Wireless sensor networks

distributed wireless sensors and communicators...

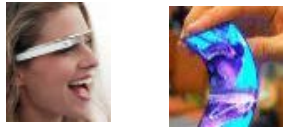
Mobile-IT

Smart watch, phones, tablets, PC's

Renewable Energy

Home storage, micro-grid storage, grid storage

Wearable and Flexible



Smart carts, patches, wearables and flexible electronics...

< mWh < < Wh < < kWh < < MWh

1E-04 1E-03 1E-02 1E-01 1E+00 1E+01 1E+02 1E+03 1E+04 1E+05 1E+06

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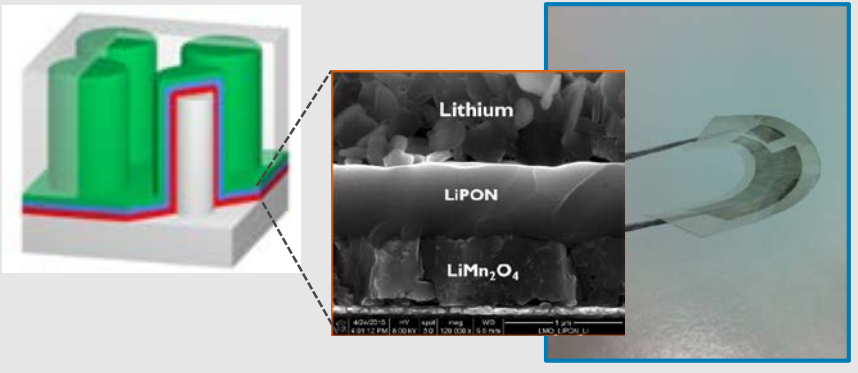
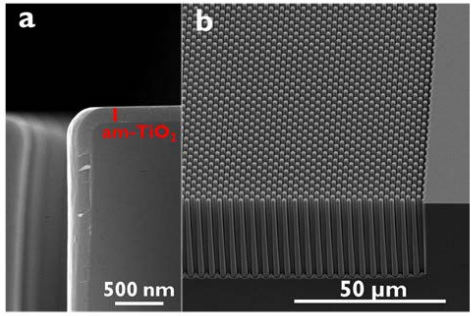
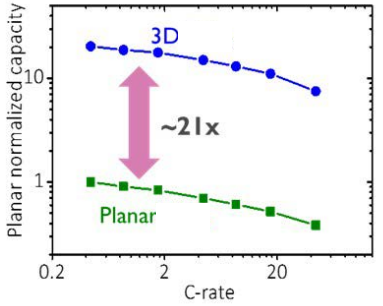
IMEC WORKS ON SOLID-STATE BATTERIES

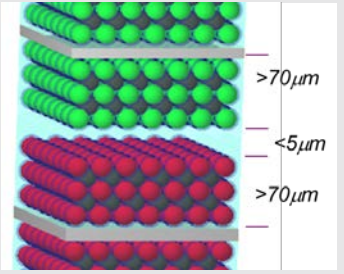
Thin-Film batteries

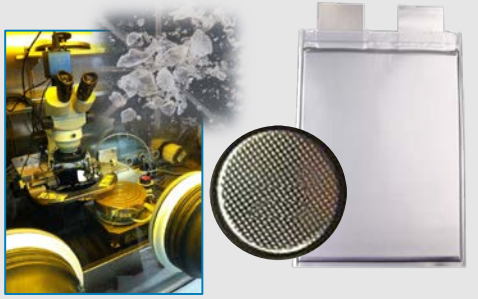




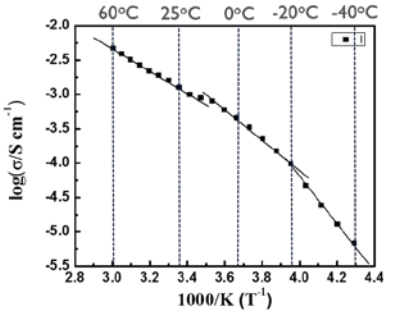


Particle composite batteries



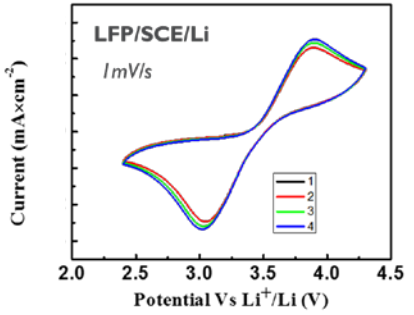


Imec nanocomposite electrolyte



σ_{Li^+} of 1mS/cm at RT

Imec Solid-state Li-ion cell



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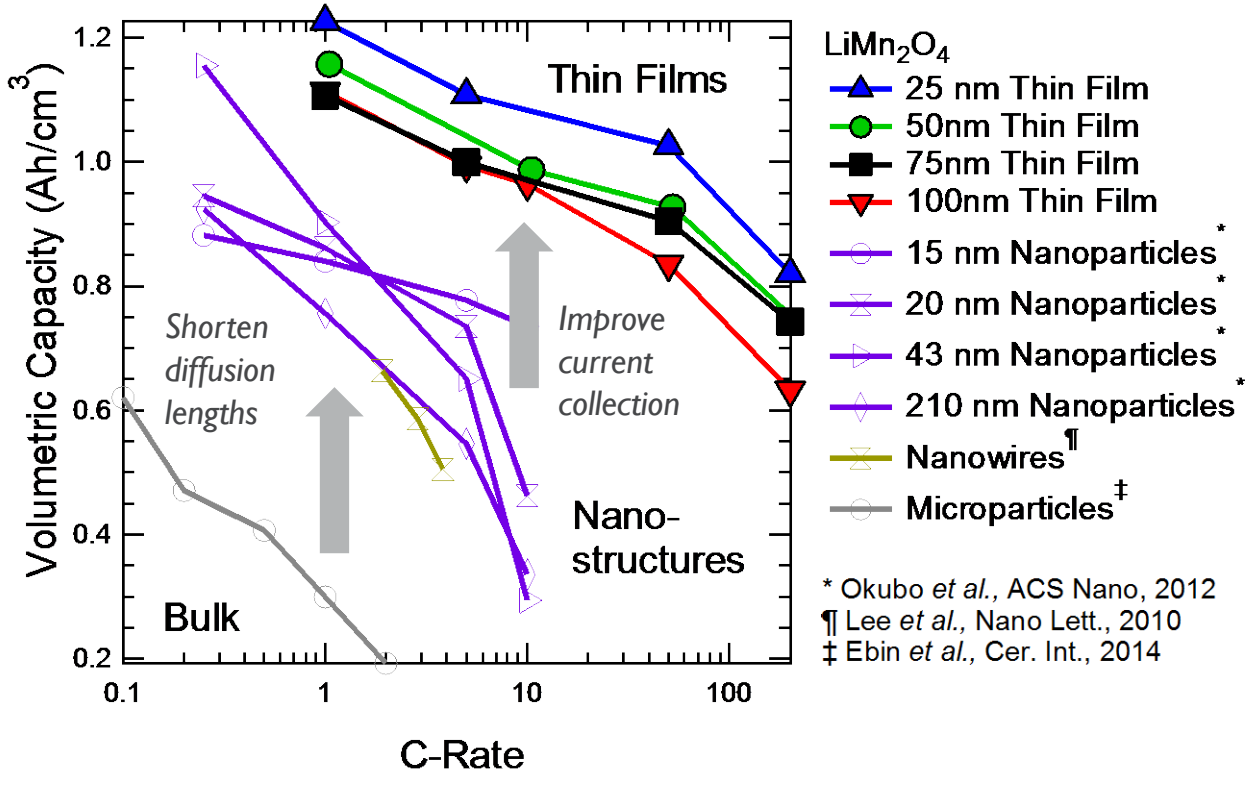
SOLID STATE ENABLES NEXT GENERATION BATTERIES
WITH NANOTECHNOLOGY

- Solid-state enables **nanoscaling** of materials *(and thus faster charging kinetics)*
  - The large surface area of nanostructures provide large surface area for fast kinetics for fast charging but also for the parasitic reactions with the liquid electrolyte (dissolution and SEI formation). These side reactions are not an issue for solid-state electrolytes.
- Solid-state enables new ways to increase **energy and power density**
  - Through compacter cells
  - Introduction of high voltage cathodes
- Solid-state enables **miniaturization and integration**
  - Micro-batteries for IoT and wearables
- Solid-state provides **safety**
  - Elimination of the flammable solvent and of the risk of leakage (implants)

IMPROVED RATE PERFORMANCE AT THE NANOSCALE

SOLID ELECTROLYTE PREVENTS DEGRADATION OF THE NANOMATERIAL

- *Example of $LiMn_2O_4$ or LMO as positive electrode with cubic spinel structure*

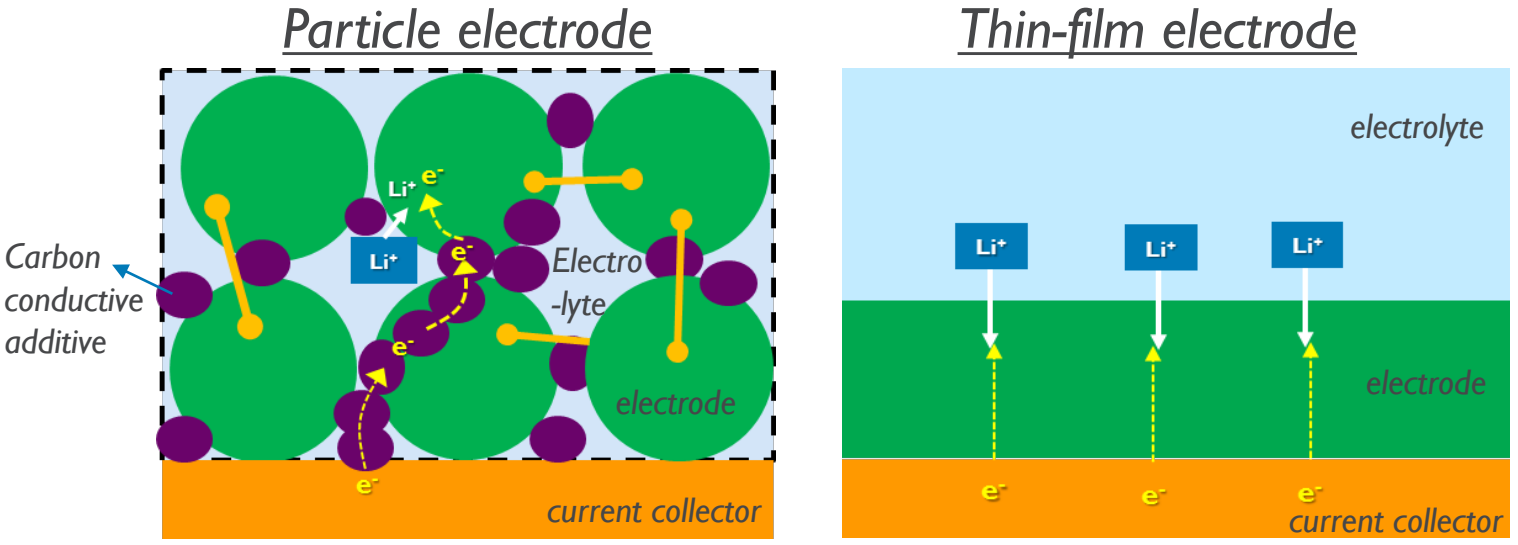


"High cycling stability and extreme rate performance in nanoscaled $LiMn_2O_4$ thin films" B. Put, P. M. Vereecken N. Labyedh, A. Sepulveda, C. Huyghebaert, I. P. Radu, and A. Stesmans, *ACS Appl. Mater. Interfaces*, **7**, 1944-8244 (2015). DOI: 10.1021/acsami.5b06386

BEST CASE CURRENT COLLECTION FOR THIN-FILMS

THIN-FILMS ARE IN DIRECT CONTACT WITH THE CURRENT COLLECTOR

- Shorter diffusion lengths for Li^+ *and* electrons provides faster charger for nanoscaled active materials (nanoparticles, nanorods and thin films)
- Good current collection is needed to fully enable the fast charging properties

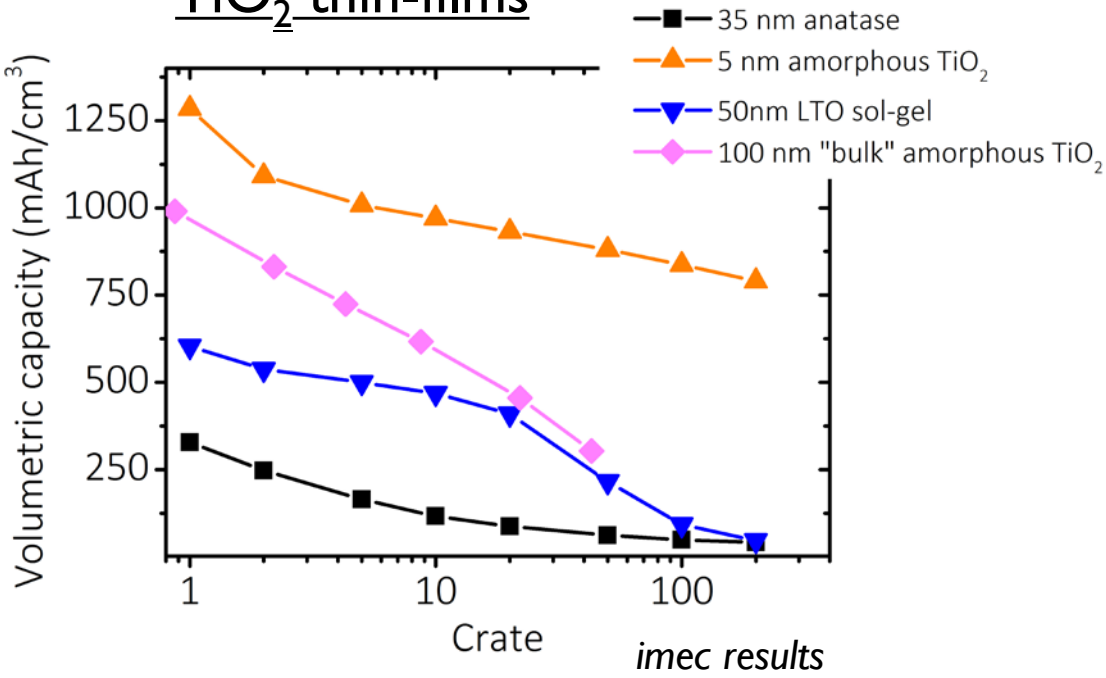


NANO-SCALING INCREASES EFFECTIVE CAPACITY

More Li-ions can be stored in truly nanoscaled materials

- Due to new stabilized phases
- Due to elimination of kinetic hindrance
- Due to mechanical stability

TiO_2 thin-films



imec results

M.Wagemakers et al., JACS, 129(14), 4323 (2007)

TiO_2 nanoparticles TU-Delft

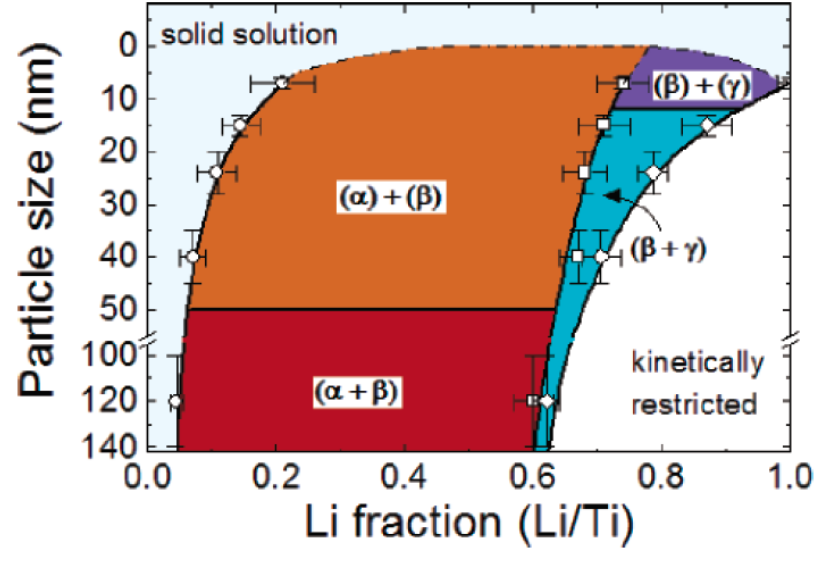
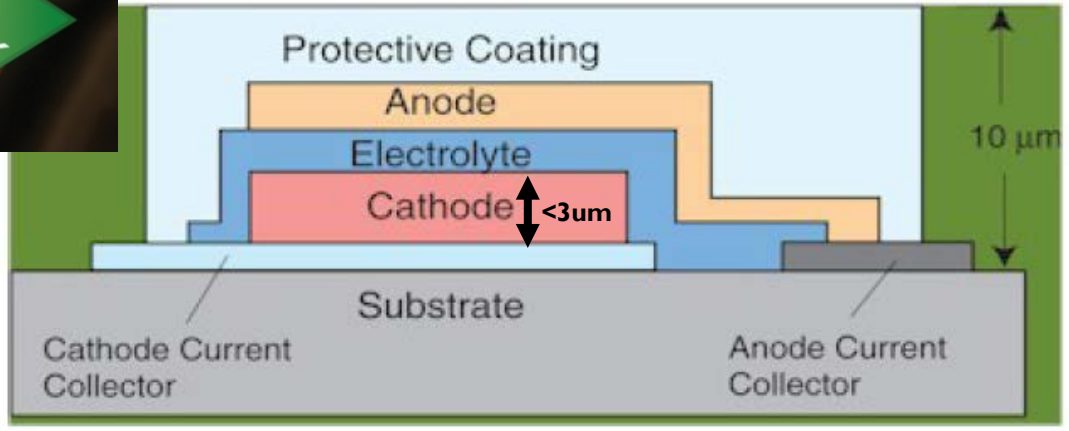


Figure 2. Phase diagram of the Li composition in anatase TiO_2 versus crystal particle size based on the neutron diffraction results. α indicates

PLANAR THIN-FILM BATTERIES HAVE LIMITED CHARGE CAPACITY

Small cells for microstorage only at this point

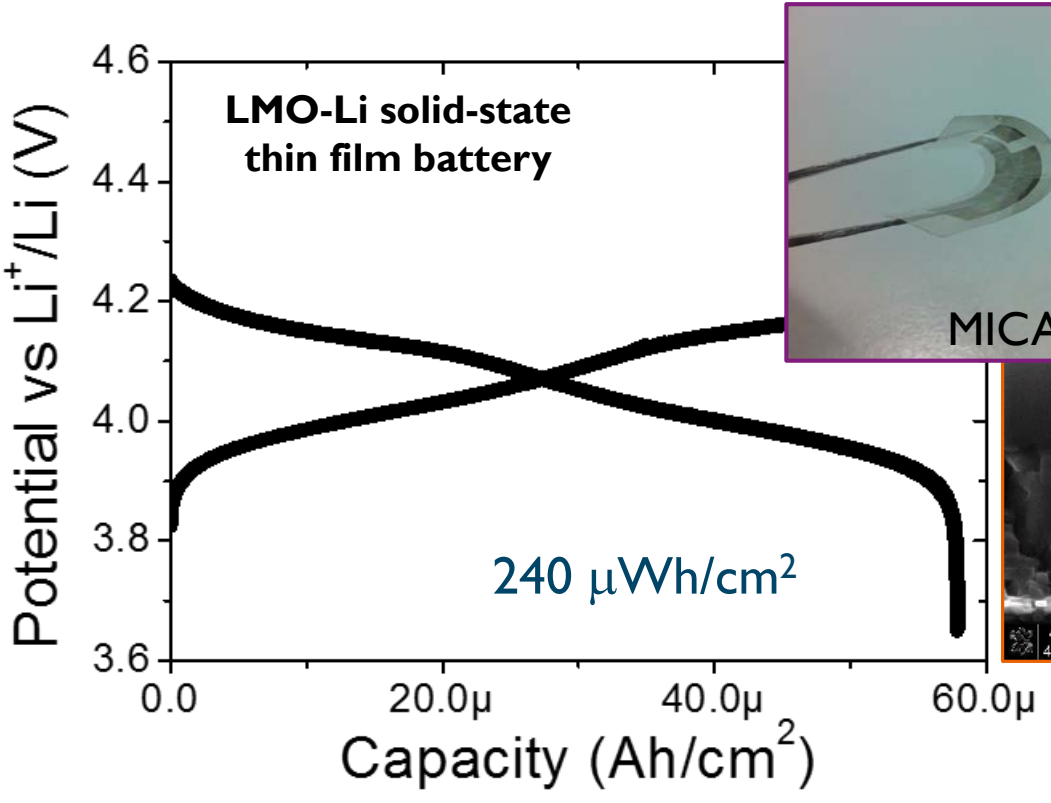
Construction of a thin-film battery. (Source: John Bates, Oak Ridge Micro-Energy).

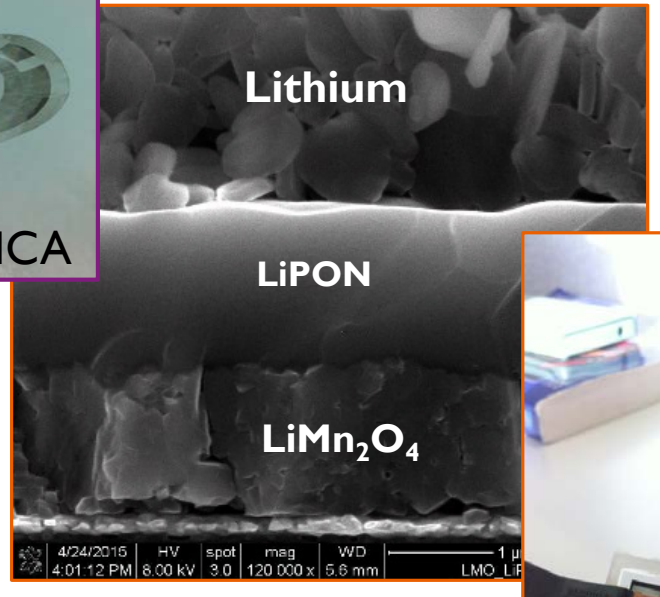


- **Thin films allow fast charging at C-rates >10C (less than 6 minutes)**
- **Charge Capacity is low (0.01 to 1 mAh) because of thin electrodes.**
- **Vacuum deposition for all layers, e.g.**
  - Cathode: $LiCoO_2$
  - Electrolyte: LiPON glass
  - Anode: Li Metal, SnN_3

IMEC 4V PLANAR THIN-FILM BATTERY, ALSO FLEXIBLE

1 μm LMO film has maximum theoretical capacity of 63 μAh/cm² (or 250 μWh/cm² against Li)



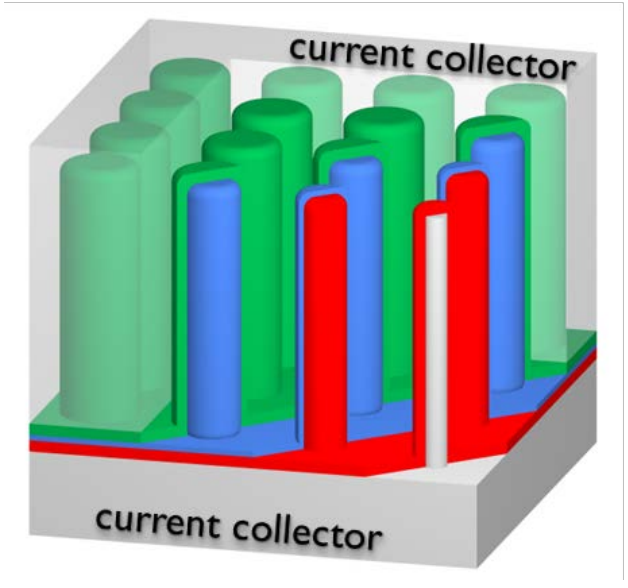


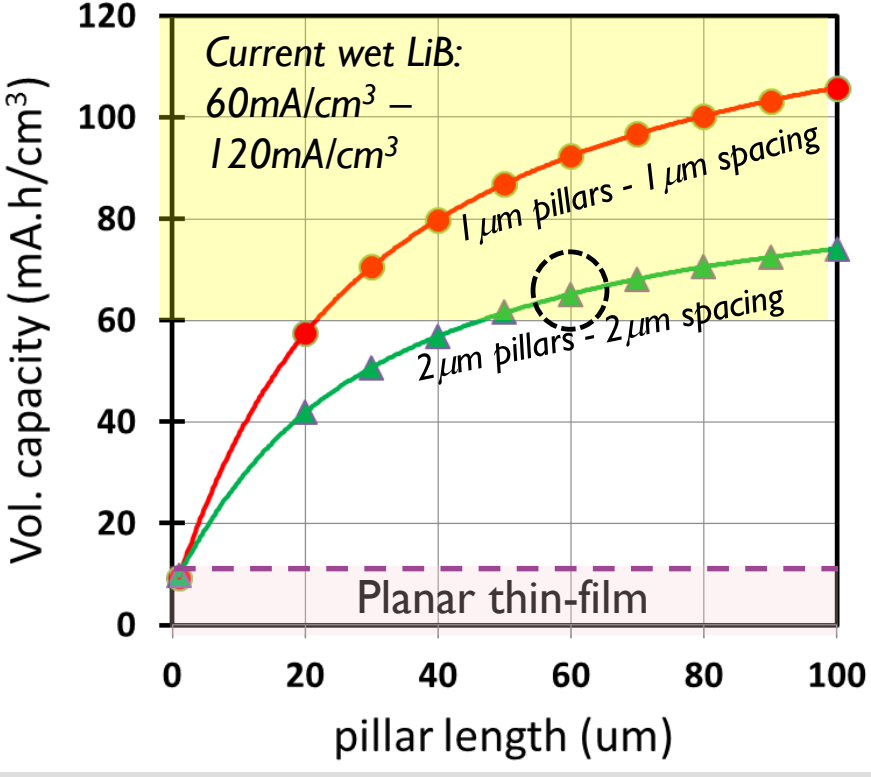
The battery stack consists of a $LiMn_2O_4$ cathode layer prepared by RF-sputtering and post treatment annealed, an electrolyte layer of LiPON prepared by RF-sputtering and an anode layer consisting of a lithium metal thin film prepared by thermal evaporation.

3D THIN-FILM BATTERIES FOR INCREASED CAPACITY

Goal of 3D patterning:

- reach the same capacity density as wet cells

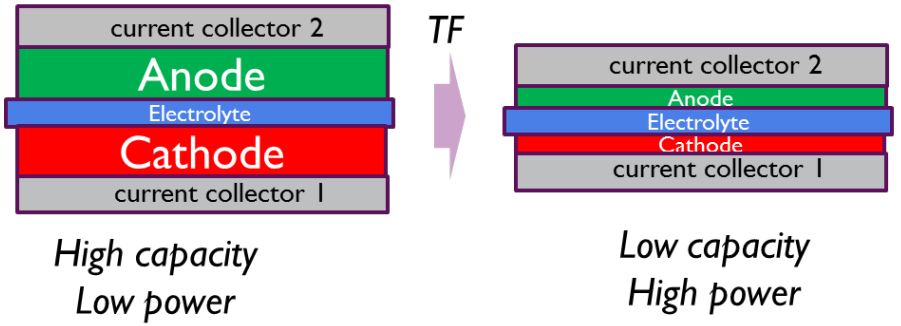




THIN-FILM BATTERIES GOING TO 3D TO COMBINE HIGH SPEED + HIGH CAPACITY

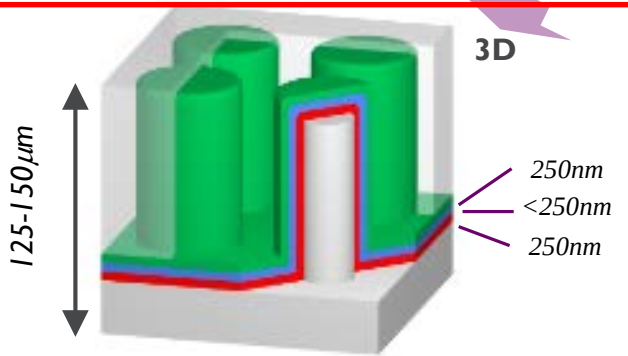
High speed:

- How: **Thin electrodes and electrolyte**
- Target: 80% capacity at 20C (3 min charging)
  compared to current 80% at 2C (30 min) wet cell



High capacity:

- How: **3D structure (micropillars)**
- Target: 60-120mAh/cm^3 (in range of current wet cells)
- Status: technologies for coating ANODE and CATHODE on high aspect ratio pillars are ready (see next slides!) – conformal electrolyte is next step



High capacity and power

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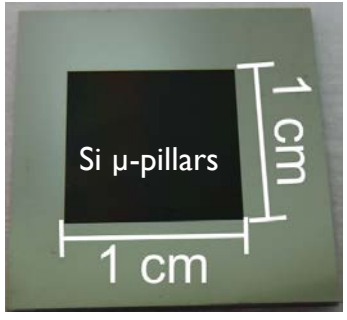
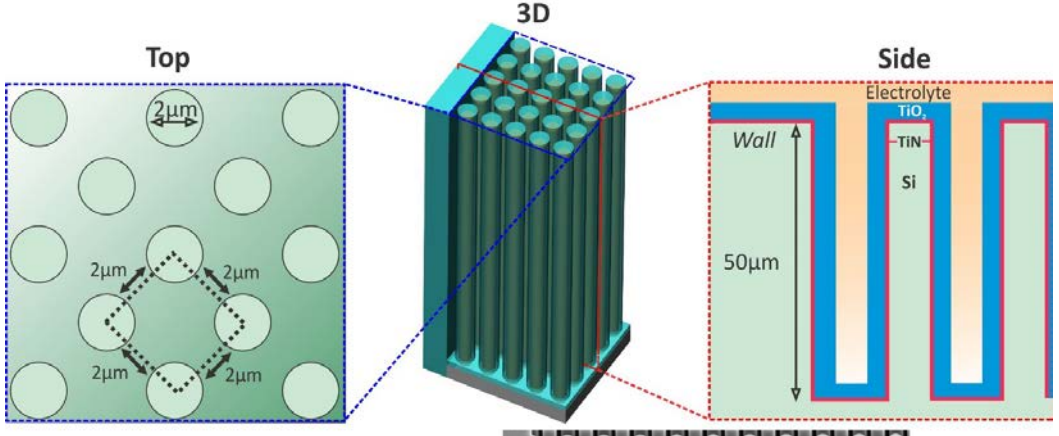
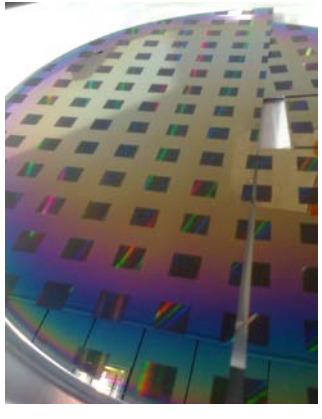
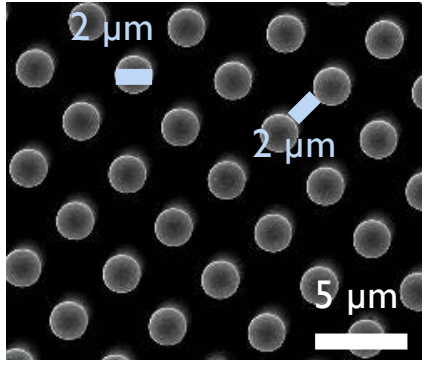
Si pillar arrays as 3D current collector substrates

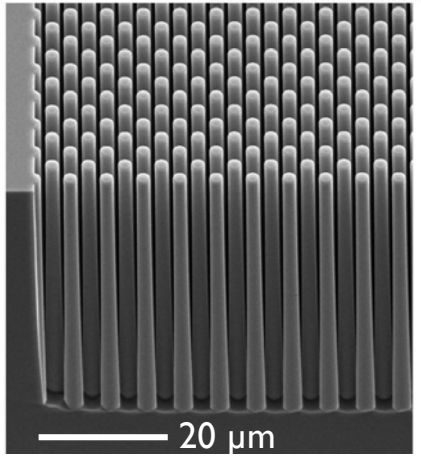
- Si µ-pillars are fabricated by lithography patterning and deep reactive ion etching on 300 mm Si wafers











50-60µm high

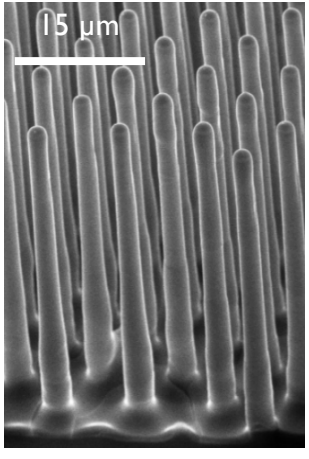
Area enhancement of 20-25x

Conformal Deposition Techniques

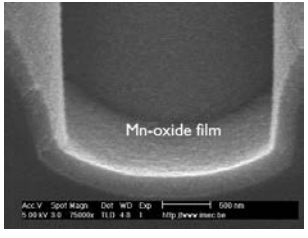
Various conformal deposition technologies developed for electrodes and electrolyte

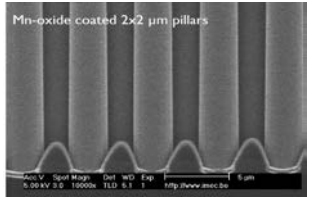
- Electrochemical deposition (ECD) demonstrated
  - Excellent conformity of adherent films
- Chemical solution deposition (CSD) demonstrated
  - Conformal coating by spray coating demonstrated
- ALD and up-scalable spatial-ALD demonstrated
  - Good conformity at practical deposition rates

Spray coated LTO pillars



ECD Mn-oxide coated pillars





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KNOWLEDGE IN ACTION

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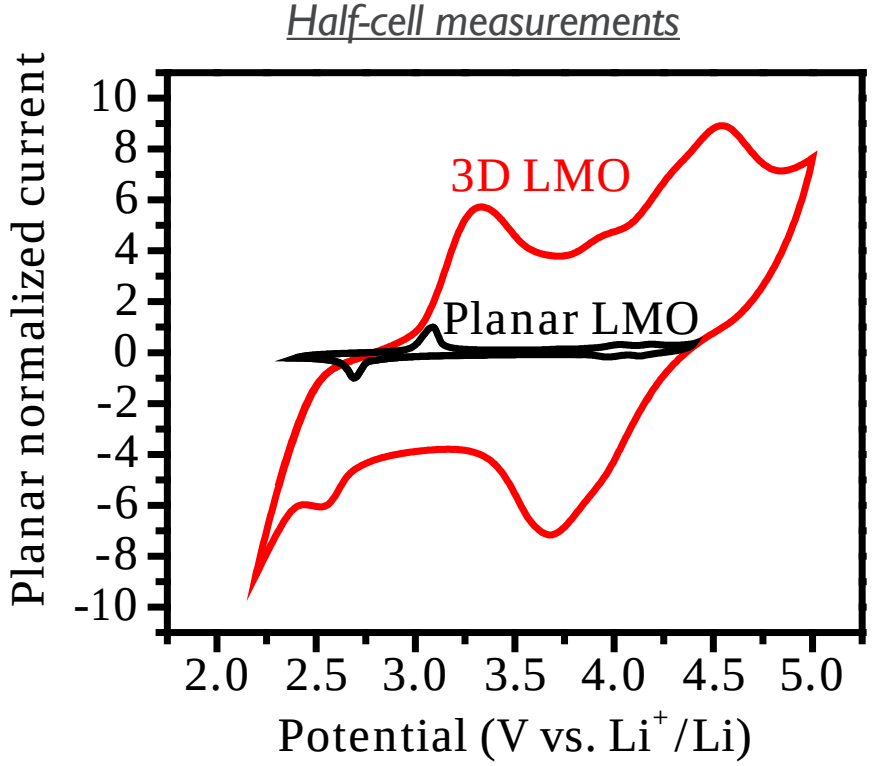
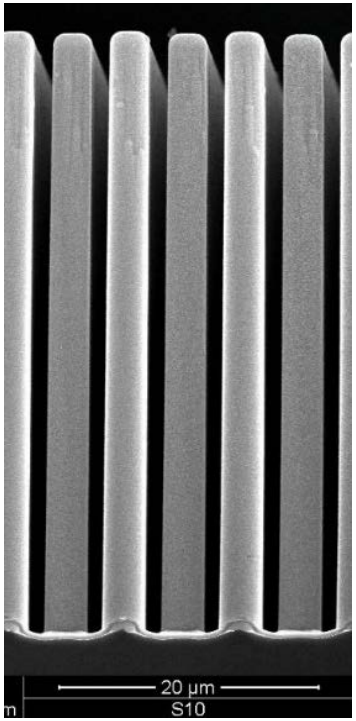
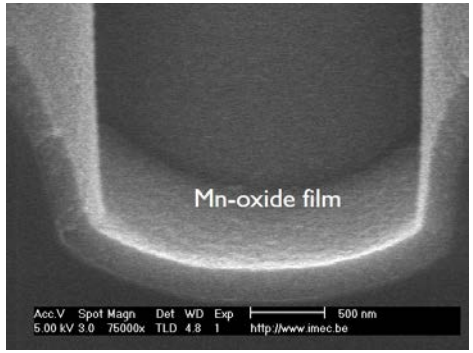
Open Innovation by imec and TNO

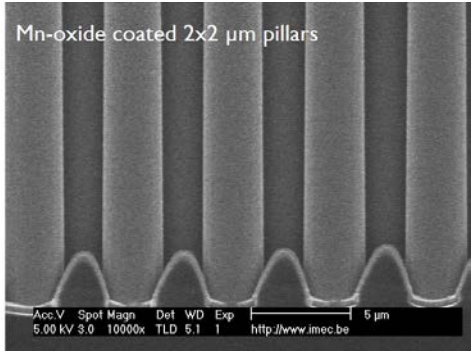
Conformal Deposition of $LiMn_2O_4$ Positive Electrode

Pillars of 2 µm in diameter with 2 µm spacing and 50 µm high: area enhancement of ~20x



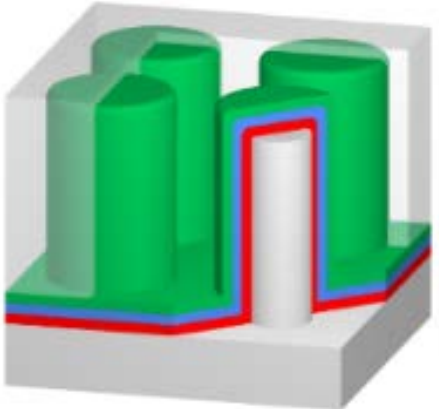




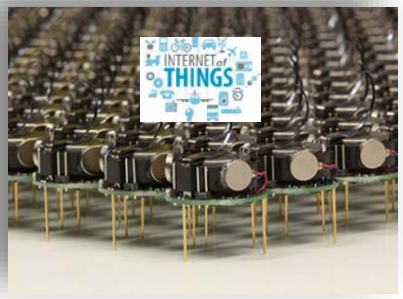


3D-TFB ENABLE INSTANT RECHARGING

- Our 3D thin film batteries enable *'Ultra Fast Charging' which is especially of interest for small electronics where space and thus battery capacity is limited* and at the same time they ensure '*Safety*', *'long battery Life-time' and 'seamless Integration' for* ***IoT, wearables, implants and smart electronics***



3D Thin-film battery



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