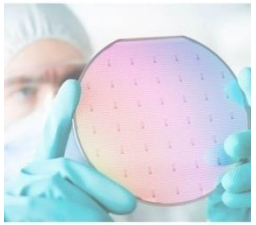





CVD Equipment Corporation

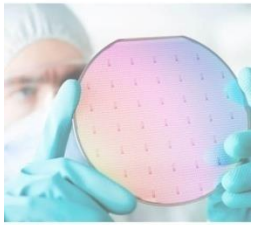
Binder-Free Battery Electrodes

Karlheinz Strobl[1*], Rune Wendelbo[2], Rahul Fotedar[2], Riju Singhal[1], and Mathieu Monville[1]

[1]CVD Equipment Corporation, New York, USA

[2]Graphene Batteries AS, Oslo, Norway

**** V.P. of Business Development, CVD Equipment Corporation***

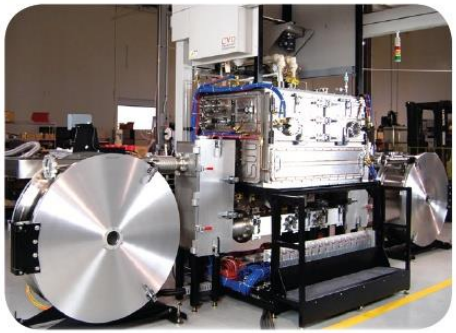





CVD Equipment Corporation

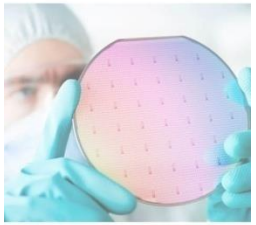
Designs and manufactures both Standard and Custom R&D, Pilot & Production chemical vapor deposition systems






Operates an Application Laboratory:

- Performs contract process development
- Develops processes and equipment for research materials
- Works with researchers to help accelerating the commercialization of nanomaterials






Commercialization of Nanomaterials

CVD Equipment Corporation

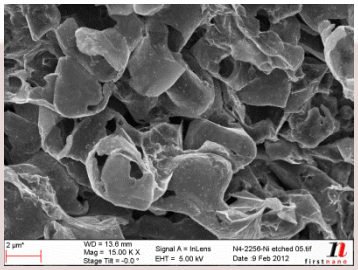
- Billions of $$$ have been spent developing a range of nanomaterials
- A Nano to Macro transformation process allows manufacturing nano-enhanced Products with higher value propositions
- $$$ can only be made at the Product level

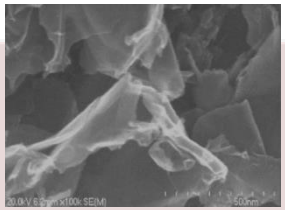
REQUIREMENTS TO DEVELOP NANO-ENABLED PRODUCTS:

- A large pool of starting nano raw materials (0D, 1D, 2D, 3D)
- A general purpose "Nano to Macro" material transformation method
- Ability to pre and post treat process materials to further tune end material properties
- Develop a scalable, low cost manufacturing process to produce nano-enabled macro sheets (roll-to-roll) with "cost effective" width and length
- Demonstrate value benefits for selected volume applications

Novel NanotoMacro™ Manufacturing Platform

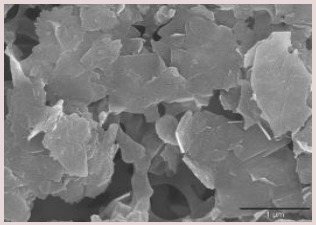
CVD Equipment Corporation





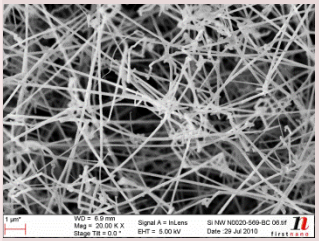
3D graphene, carbon-derived-carbons, hollow carbon structures, etc.

3D



Nano platelets: graphene vermiculite, clay BN, MoS_2, …

2D

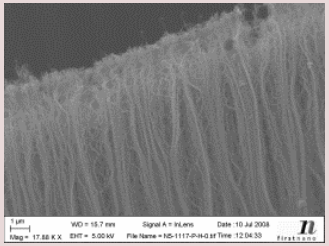


Nanowires: Si, GaN, BN, TiO_2…

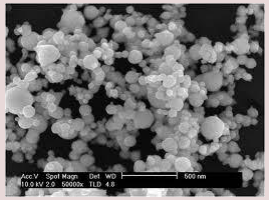
1D

Nanotubes: VACNT, BN NT

0D

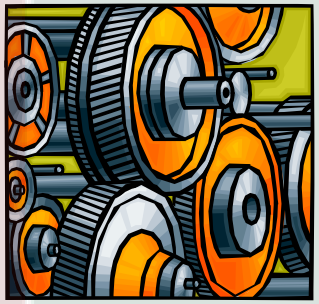


Nanoparticles: $LiFePO_4$, …,

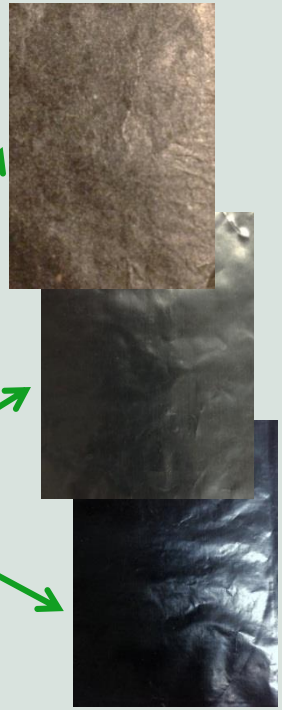


Raw nanomaterial manufacturing process

NanotoMacro™ Manufacturing Platform



Sheet manufacturing process



- Larger range of nano-enabled macroscopic material formulations
  Economical manufacturing process
  no high-temperature step
- Universal process for a wide range of nano materials

OPTIMIZABLE FOR:

thickness

surface density

density

electrical conductivity

thermal conductivity

surface area

capacitance

fire retardant

high temperature durability

UV-FIR absorption

mechanical interlocking

shock absorption

compression resistance

strength, etc.

Novel Nano*to*Macro™ Manufacturing Platform

CVD Equipment Corporation

"The paper route applied at the nanoscale":
What are the technical advantages of papermaking?

Well-known vacuum-filtration method

Louis-Nicolas Robert's 1st papermaking machine

Batch processing

Roll-to-roll engineering

Integration of additives or additional processing steps

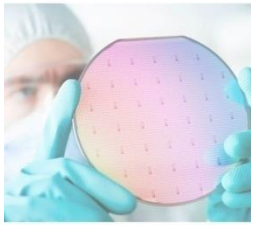
In-line manufacturing capable

Easy-to-tailor to the required specificity of the end product

Recyclability / greener processing

Scalability

Today's industrial scale papermaking machine





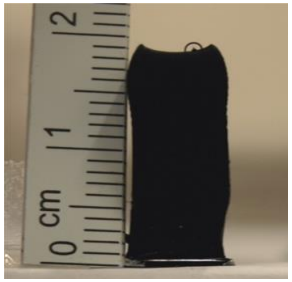

Nanocarbons can be both "Active Materials" and "Binder Materials" for Batteries and Supercapacitors

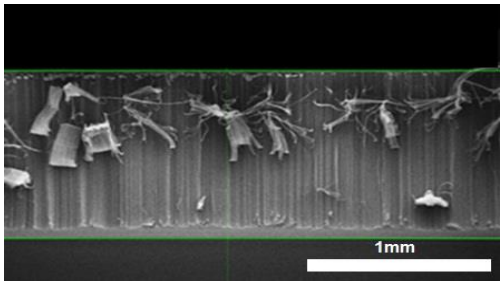
CVD Equipment Corporation

The aim of the carbon community is to create functional materials, having enhanced properties, using less materials with simpler and more environmental-friendly processes.

Our vision (binderless nano enabled sheets)

mm-long MWCNTs/SWCNTs can be utilized to form ***3D mechanical and electrical nets binding any other active*** material (carbon or non-carbon) together without the need for polymers



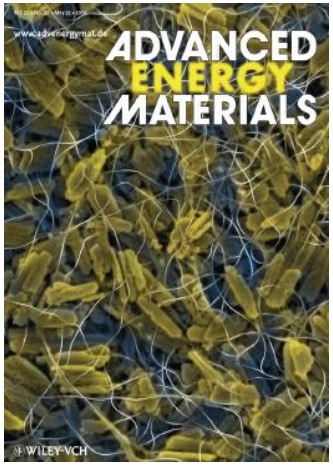


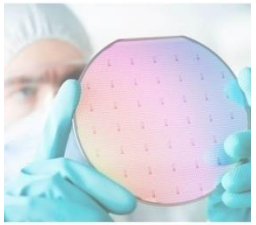
VAMWCNTs, removed from growth substate

The "paper" platform route utilizing mm-long CNT's as 3D net enables the manufacture of many multifunctional nano-enabled materials.

Related concepts: NREL

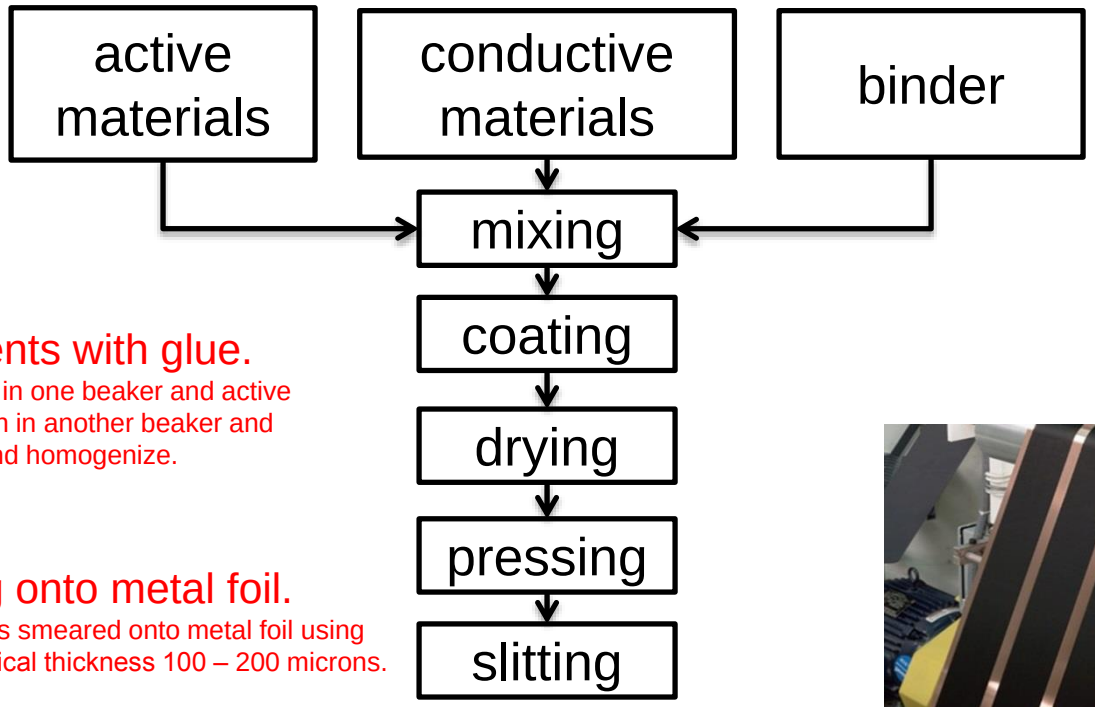
- C. Ban, Z. Wu, L.Chen, Y. Yan, A.C. Dillon *Adv. Mater*. 2010, 22, E145–E149
- US 2011/0070495 A1
- US 2011/0111279 A1








Traditional Battery Electrode Manufacturing

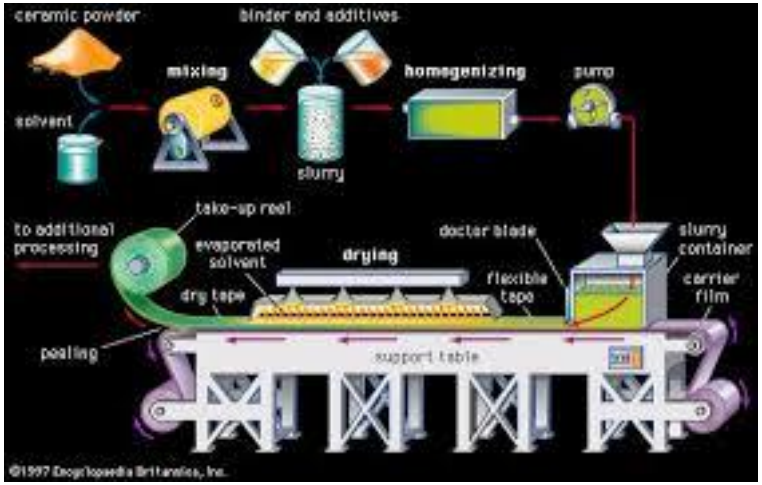


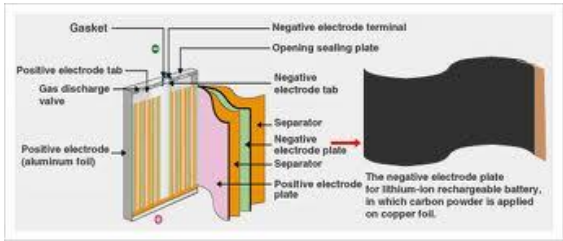
Step 1.
Mix ingredients with glue.

Make glue solution in one beaker and active material and carbon in another beaker and then mix the two and homogenize.

Step 2.
Calendaring onto metal foil.

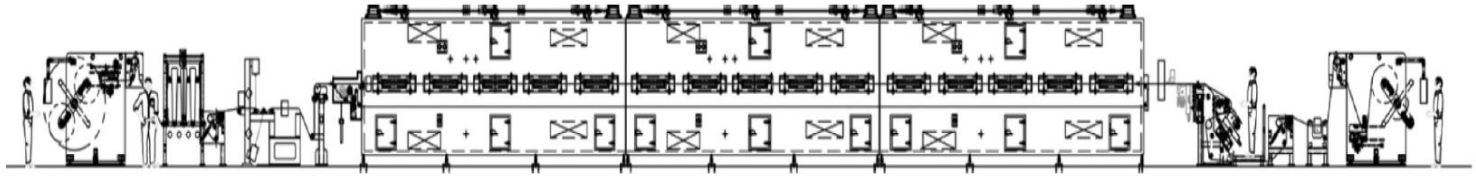
Slurry from step 1 is smeared onto metal foil using "doctor blade". Typical thickness 100 – 200 microns. Then let dry.





Problems of Polymeric Binders in battery electrodes!

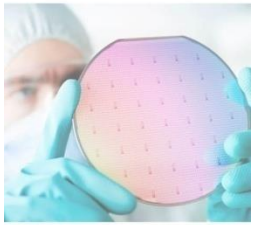
CVD Equipment Corporation



- Lithium Batteries Manufacturing typical used large amounts of
- toxic chemicals (NMP) to dissolve binders (70% of slurry)

- Requires special facilities (10-100 m tall chimney) to exhaust, dry and recover toxic solvent vapors:

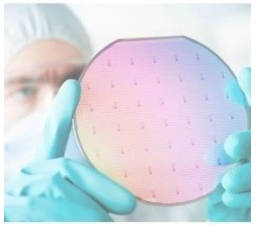
-> capital intensive and high operating cost






Polymeric Binders limit performance in battery electrodes!

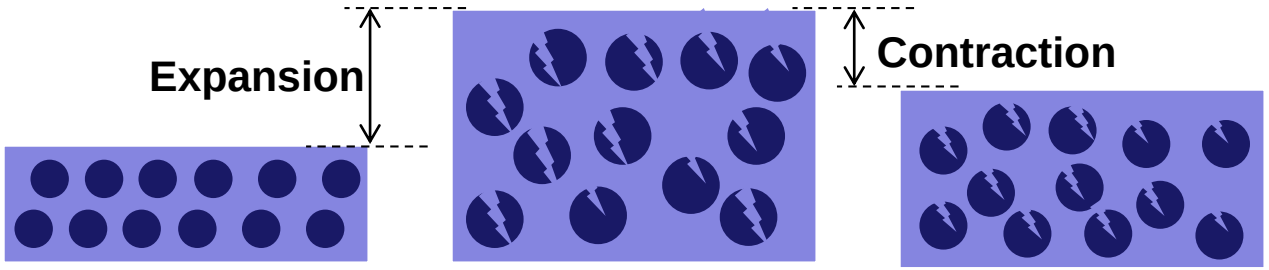
- Reduce conductivity of electrodes
- Limits the practical usable thickness of electrode for given C rate
- Can swell over time and thereby limiting the battery life (especially with ionic liquids)
- Result in low lifetime (100 cycles) for higher capacity active materials that have large volume changes (Si, Sn, etc.)



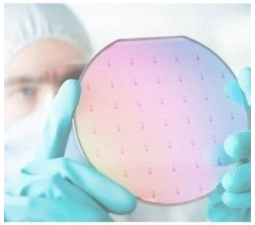



Li-Ion Batteries: Recent Developments

- Developments in this field were slow until recently when significant increase in cell capacity was demonstrated by inclusion of Si (and other entities capable of repeatedly alloying & de-alloying with Li)
- However, expansion-contraction makes particles disintegrate and lose electrical contact
- Further, expansion-contraction is not reversible resulting in a net volume change.
- Therefore: binders which are used to hold electrode material in place are one potential area for improvement.



- Partial Irreversible Expansion-Contraction cycle
- => Particle disintegration






Li-Ion batteries: Need for new binder materials

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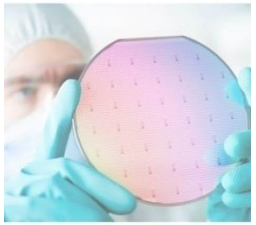
- Binders used for batteries in portable devices should be thermally stable for temperatures which sometimes exceed 250 ºC
- Fluorinated binders commonly used pose an environmental risk
- The most popular binder PVDF can excessively swell and requires volatile and toxic solvents (e.g. N-Methyl Pyrrolidone)
- Binders should preferably be electrically conducting so that the resulting electrode material has higher electrical conductivity

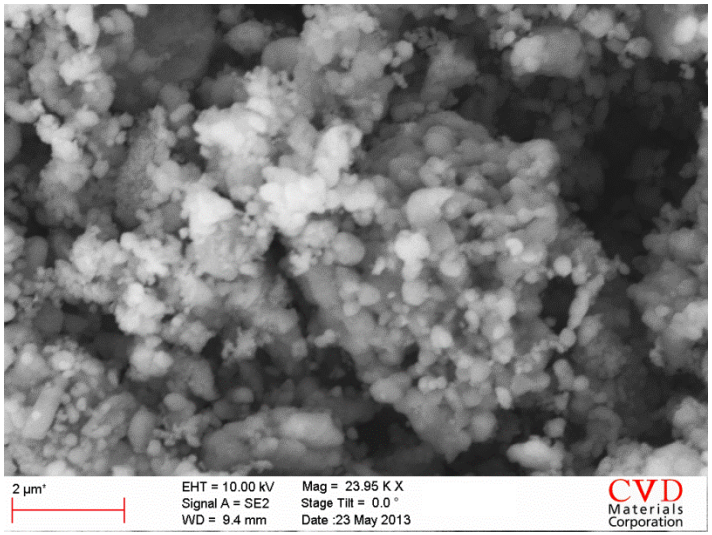
=> Millimeter long CNTs offer high strength, flexibility, porosity and high electrical conductivity, making them a suitable candidate for binder material

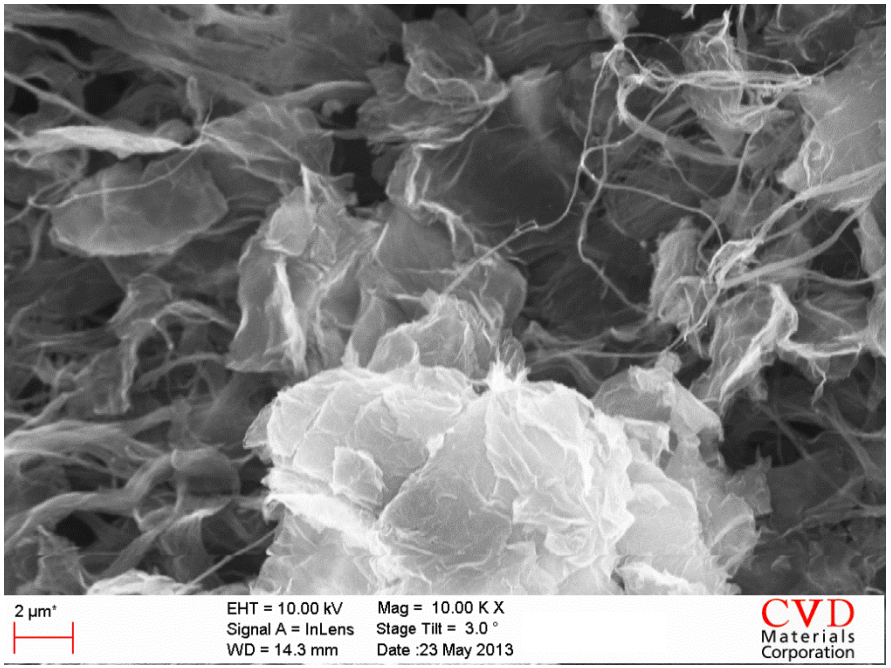


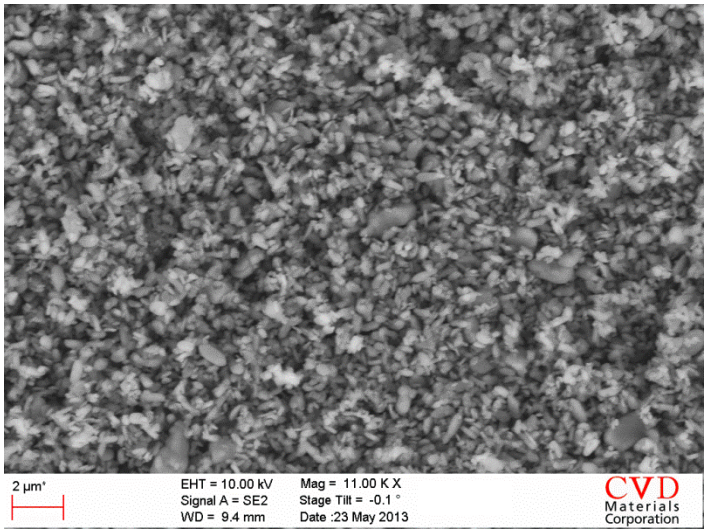



Converting different size LFP powder to "paper"-like sheets

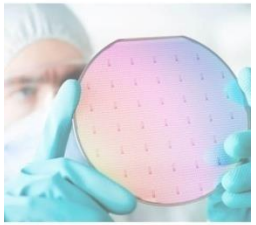
CVD Equipment Corporation







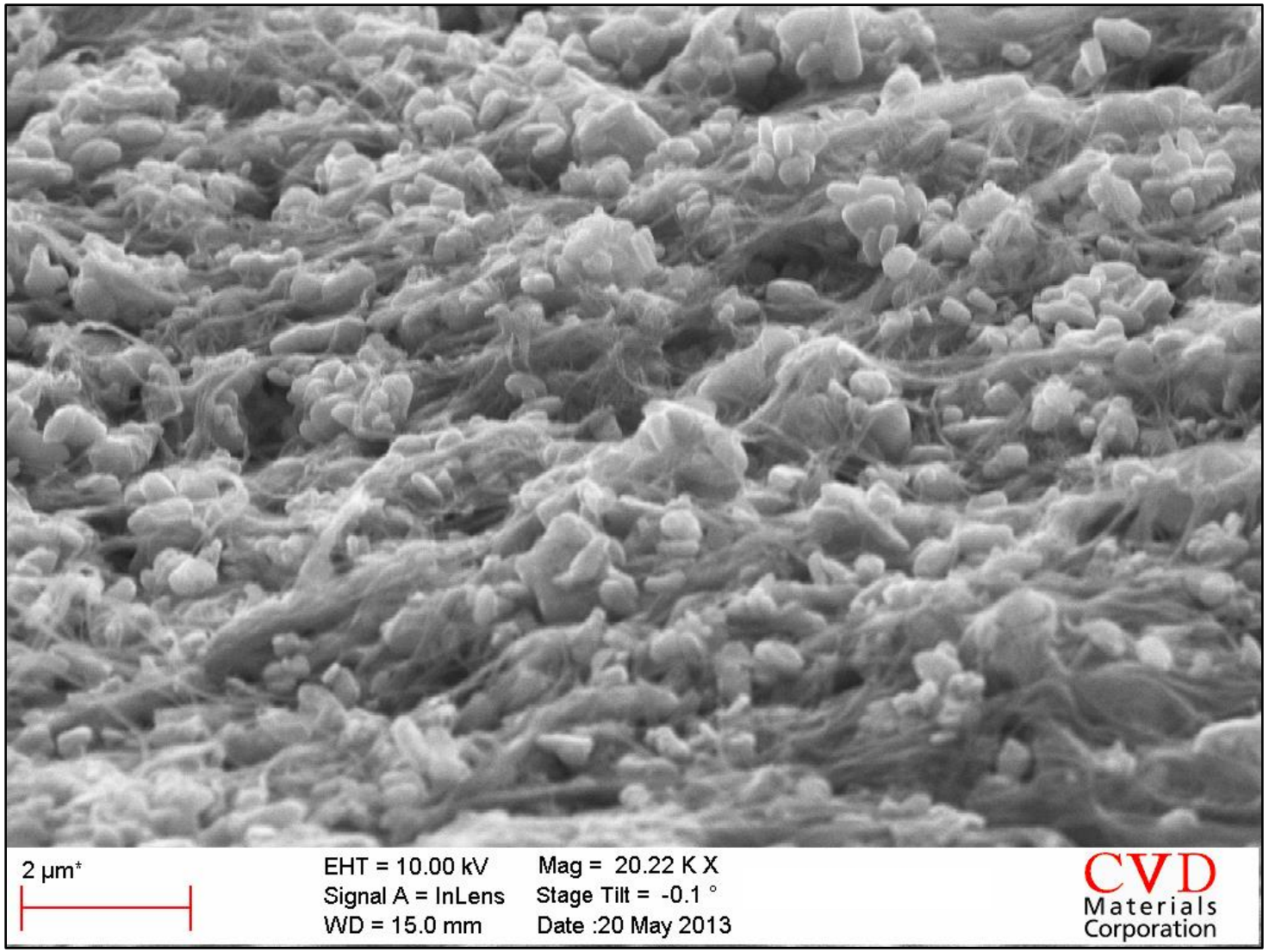
mm-long CNTs trap active nano/micro material
in electrical and mechanically interconnected 3D net






Binder-Free Battery Electrodes

CVD Equipment Corporation



8% mm-long CNTs + 92% Lithium Iron Phosphate

Binder-Free electrodes bonded Binder-Free to metal foil

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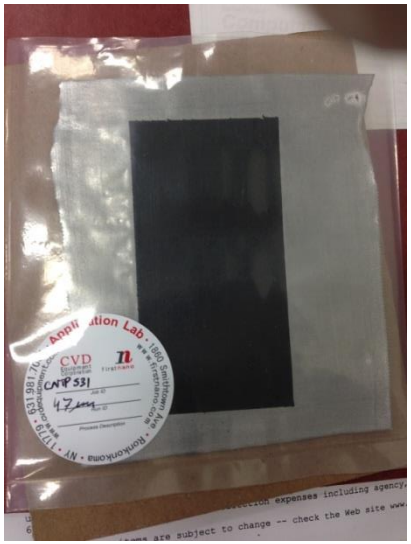


Binder-free bonding of
Binder-free electrodes to
Current conductor

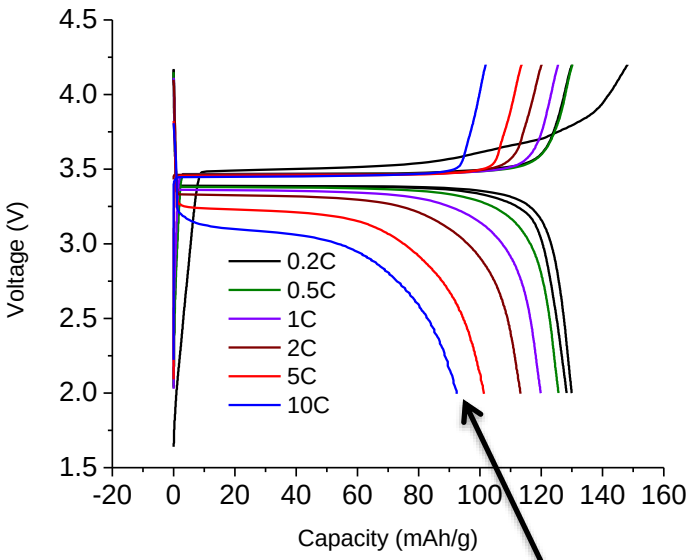
- *More active materials*
- *Better conductive network*
- *Tunable tortuosity*
- *No polymeric binder*
- *Thicker electrodes possible*
- *Flexible electrode possible*
- *New type of current collector possible*

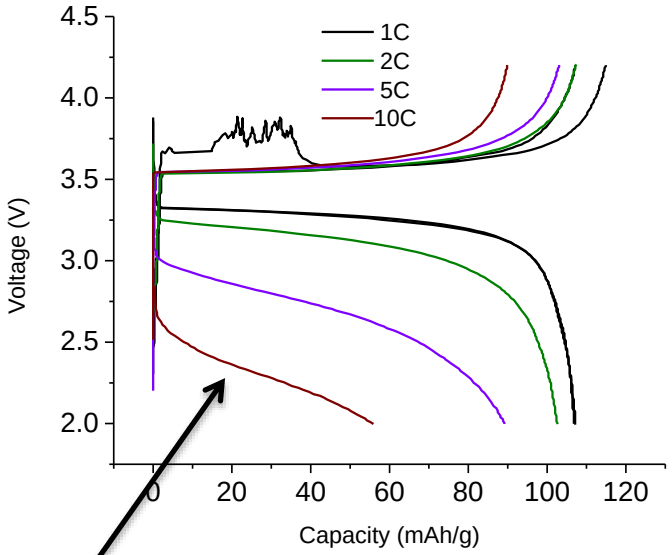
Working Towards
1) binder-free technology
2) thicker electrodes
3) longer life
3) higher energy densities
4) Higher power capacity devices

www.graphenebatteries.no

C-rate testing of half cells

PRELIMINARY DATA





Binder-free electrode
LFP 92%, CNT 4%,
CB 2%, rGO 2%, 35mg/cm^2

Reference electrode (LFP 80%, 10% CB, 10% binder), 5-6 mg/cm^2

Shows higher rate capability for similar charge capacity

PRELIMINARY DATA

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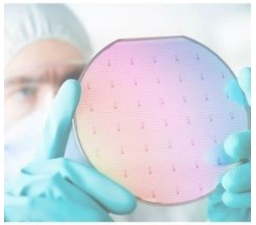




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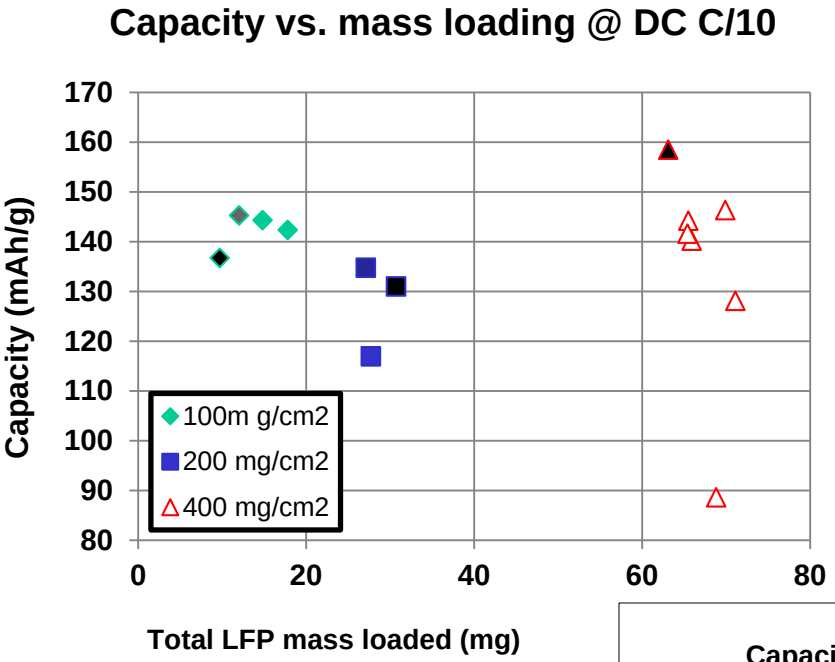
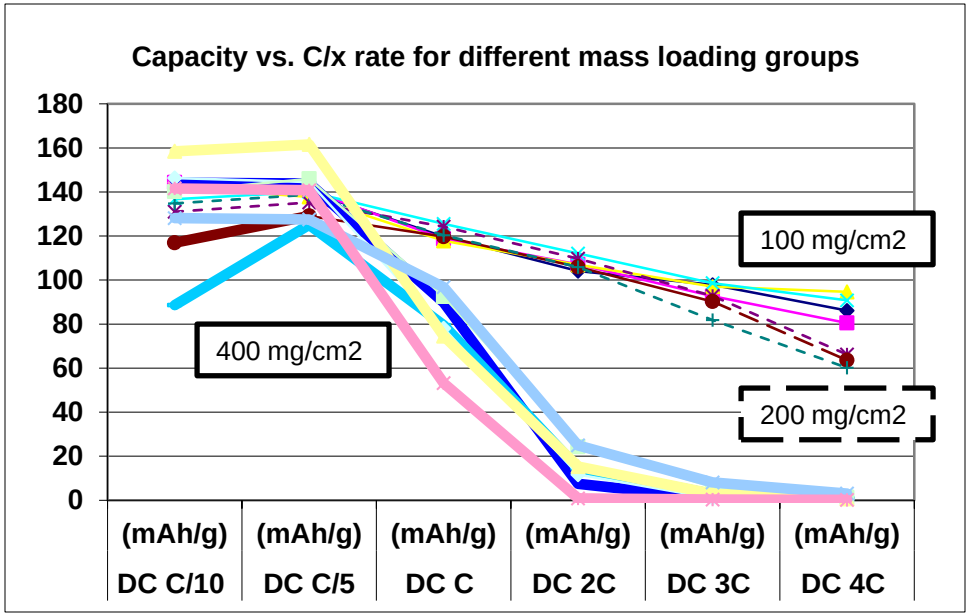


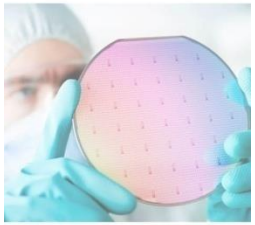
Process uniformity needs to be improved!

Thicker electrodes possible.

Thicker electrode need more vertically aligned pores to increase electrolyte Transport.

Delamination between Current conductor and Binder-less Electrodes under investigation, mixed data at 200 cycles.

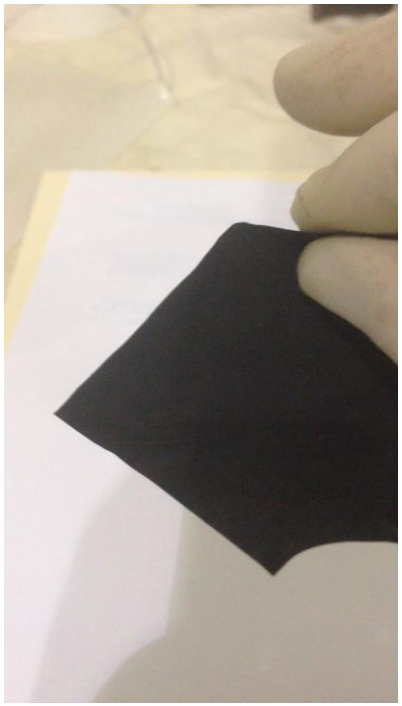


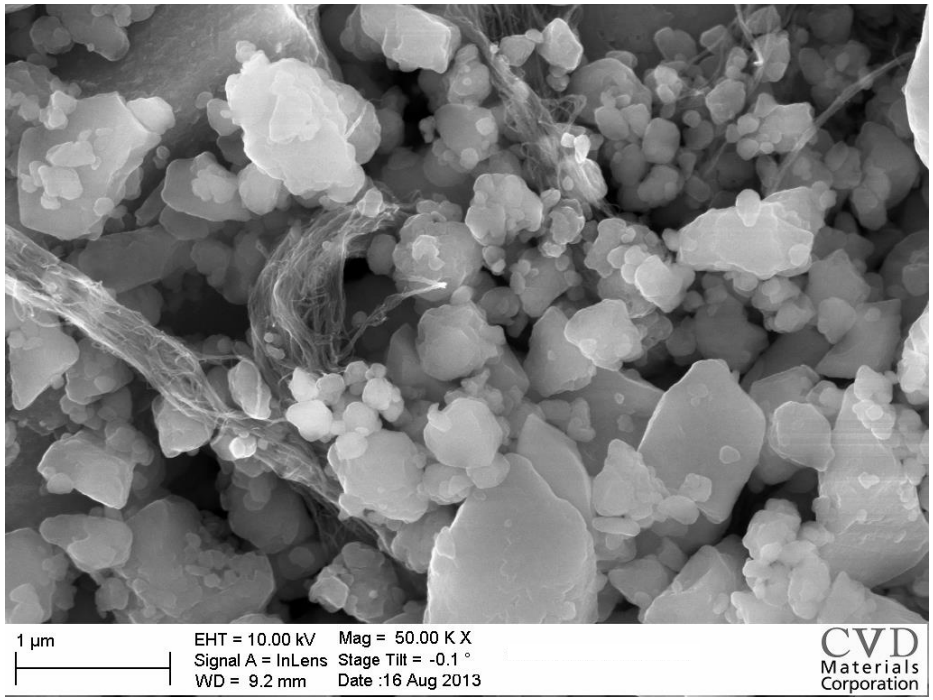





Binder-Free Si-sheets with mm long CNTs

CVD Equipment Corporation





mm-long CNTs trap active Nano sized Si powder
in electrical and mechanically interconnected 3D net

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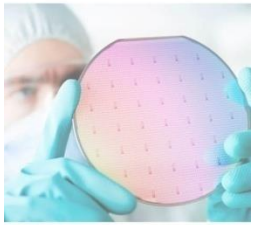




CVD Equipment Corporation

Summary:

- CVD Equipment Corporation continues to expand capabilities in
  - Equipment design
  - Process development
  - Material applications
- CVD Application Laboratory supports custom process and material development opportunities to advance the state of the art.
- We now leverage a growing range of nanomaterials developed in-house and manufactured by others.
- Our low cost, **Nano*to*Macro™** sheet manufacturing process is highly flexible and can manufacture many different types of multifunctional materials.
- Binder-free battery electrodes are possible and are under further investigation!

Thank You!

What material / application problems can we help solve for you today?

www.cvdequipment.com www.cvdmaterialscorporation.com