Materials and Structural Design for Advanced Energy Storage Devices

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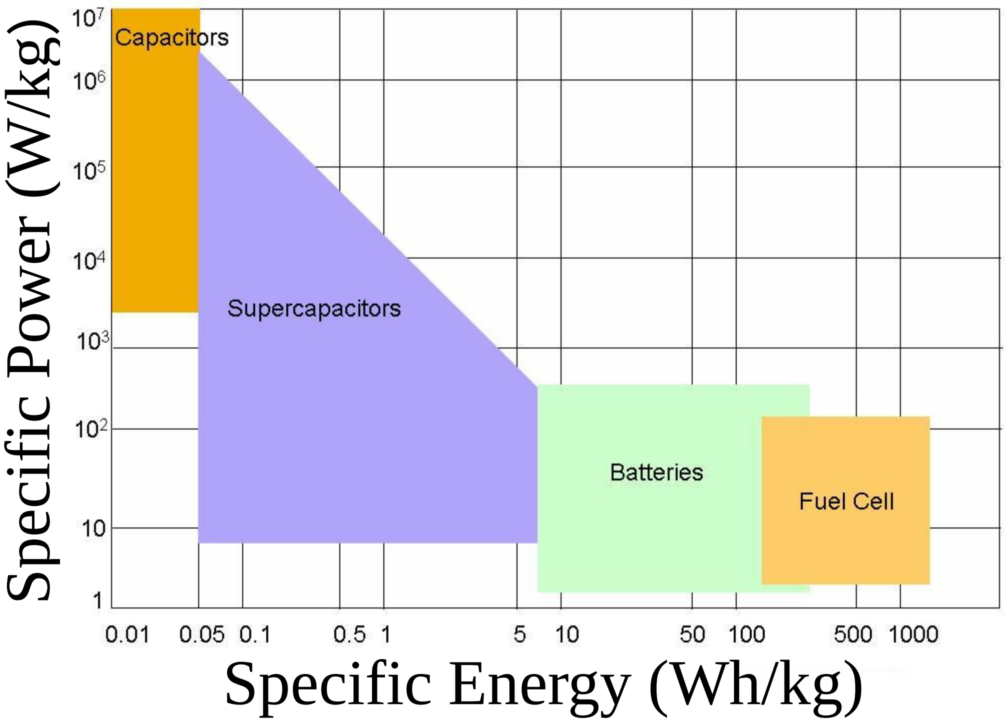
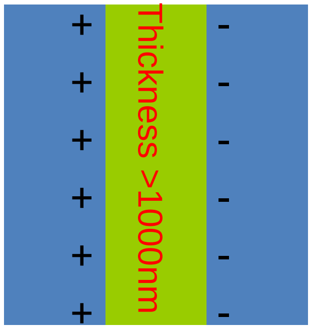
Introduction and Motivation

Portable electronics

Electrical vehicle 20-30% CO_2 emission



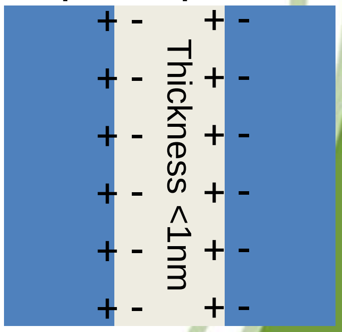
Capacitor



$E = \frac{1}{2} CV^2$

C α 1/thickness

Supercapacitor



Electrolyte solution

Important Parameters:

1. Energy and Power density
2. Cycle life and safety
3. Cost

Supercapacitors

Electric Double-Layer Capacitors

+

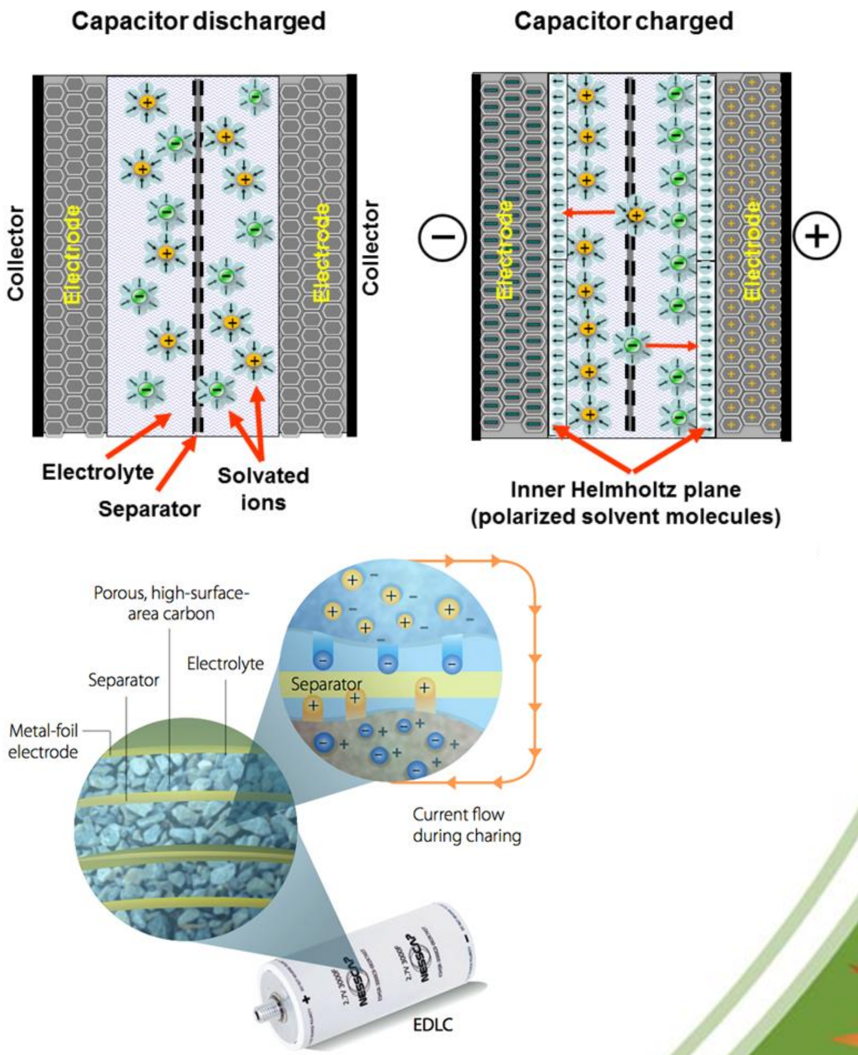
Pseudocapacitors

=

Hybrid Capacitors

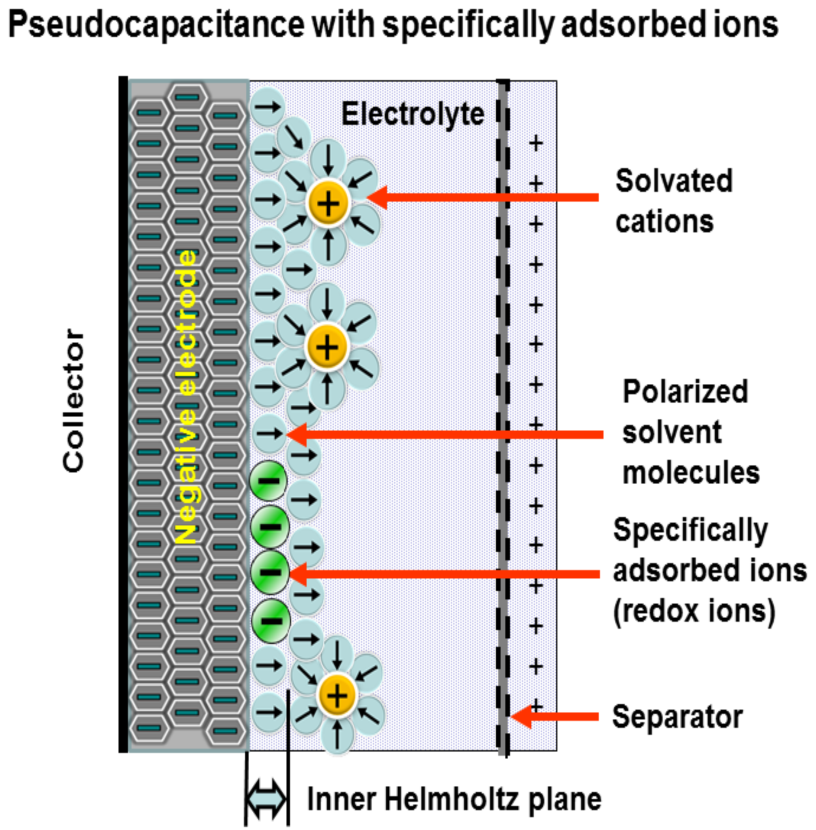
Electric Double Layer Capacitor

- EDL formed with electrode and electrolyte with solvent molecules between as dielectric.
- Store energy by adsorbing electrolyte ions onto the surface of the electrode
- Fast acting. Low energy potential, charge confined to surface



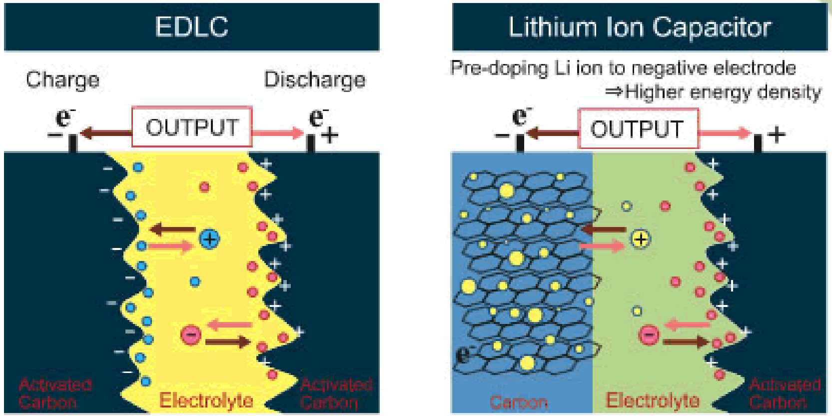
Pseudocapacitor

- Rely on redox reactions that take place at the electrode
- Electrode materials typically made up of transition metals, conducting polymers, or compound with O and N functional groups
- Higher Energy density but lower cycling life

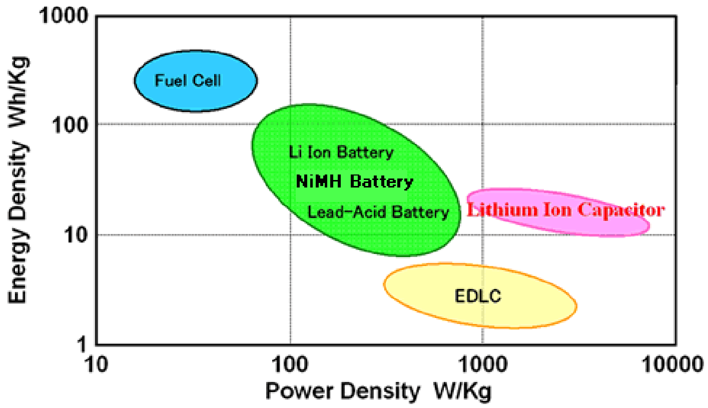


Hybrid capacitor

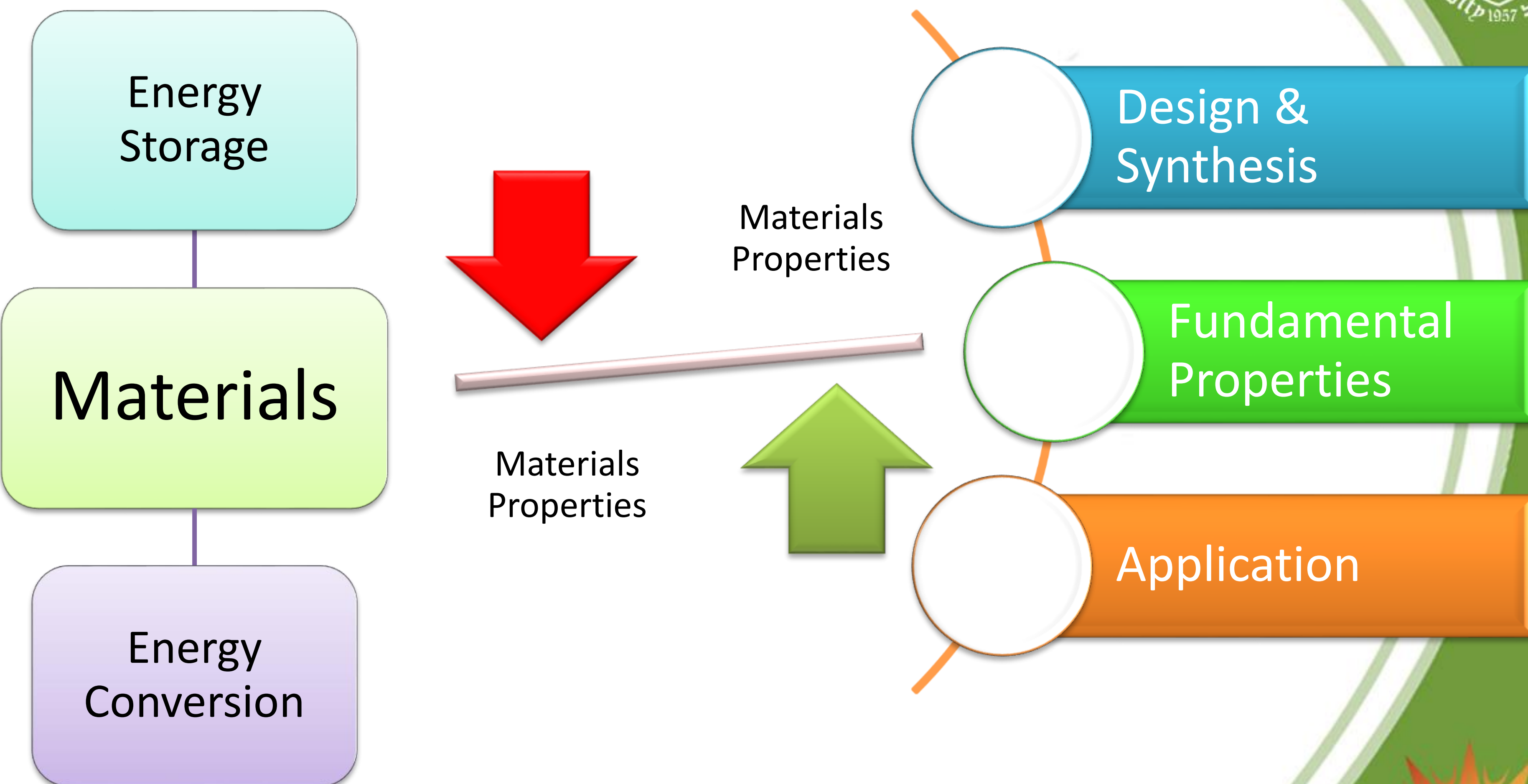
– A combination of EDLC and pseudocapacitors. Optimizes power density of EDLC with energy density of pseudocapacitor



– One common example is the Li ion capacitor which is a current leader in the field



Design Considerations



A balance between different materials properties is highly desirable for ultra efficient devices for energy storage and conversion devices

Materials Challenges

Reactions occur at the electrode surfaces

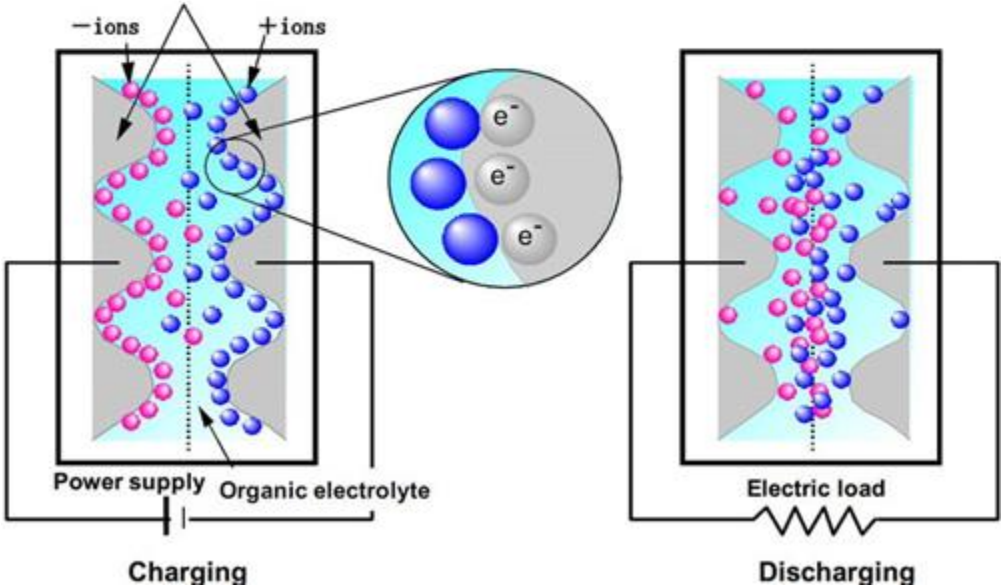
- ✓ We want to get as high a surface area as possible
  - Need to have ions and electrons together for reactions to occur
  - However
  - e.g. Nanomaterials behave differently than bulk materials
    - Energy of the reactions also depend on the surface properties
- ✓ Electrons must still be able to get outside the cell
  1. Electron resistance cannot be too high
  2. Separator must be robust and allow rapid transfer of ions
  3. Fundamental materials properties need to be understood

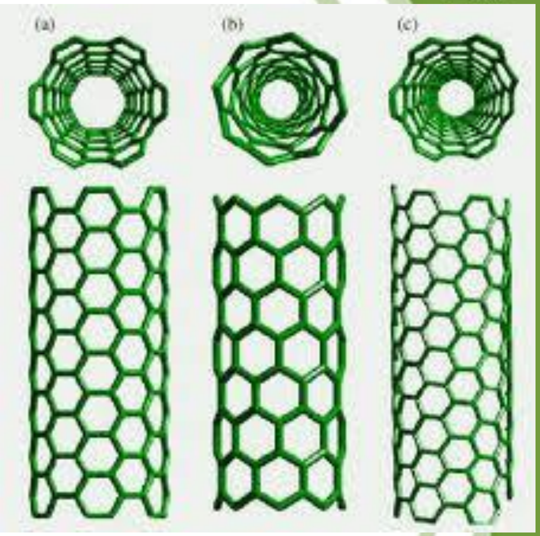
Basic materials properties

1. Transport in porous materials
2. Interfacial properties

Materials for Supercapacitors

Double Layer Capacitors

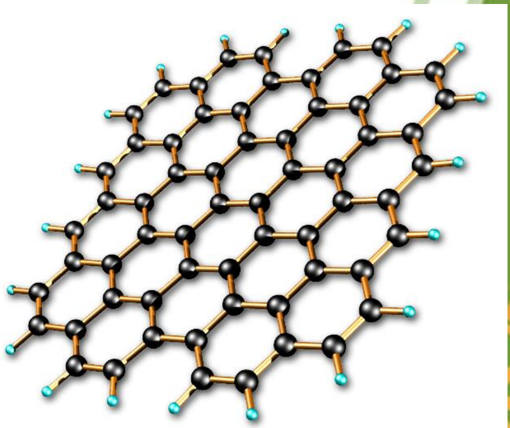




CNT$_S$

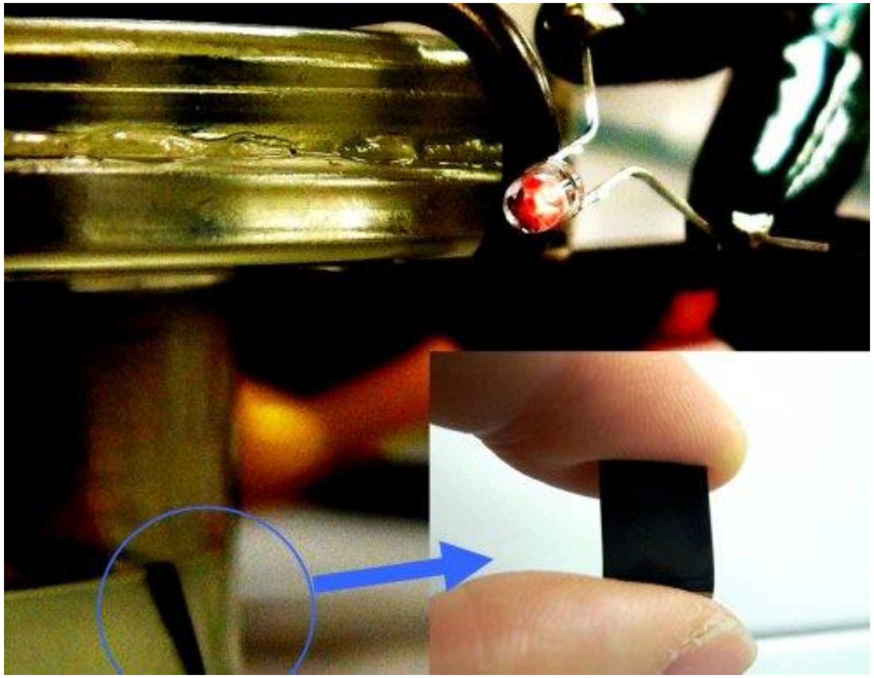
Carbon Aerogel

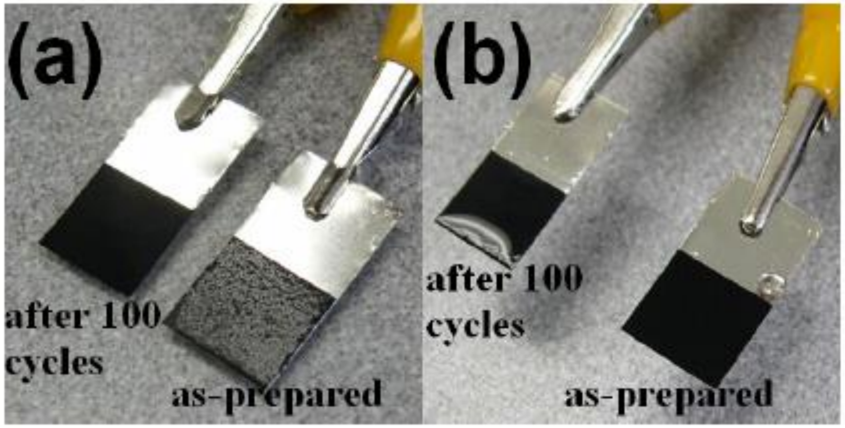
Activated Carbon

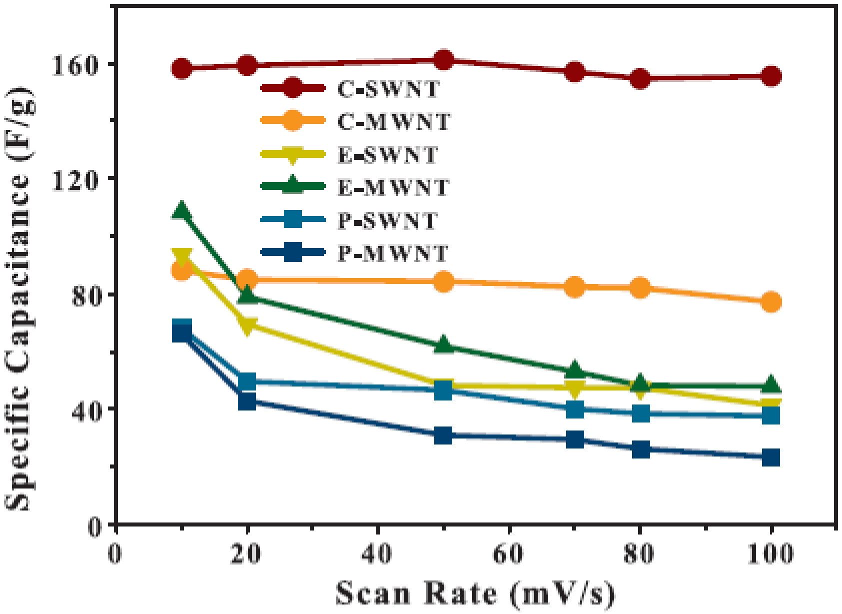


Graphene

CNTS

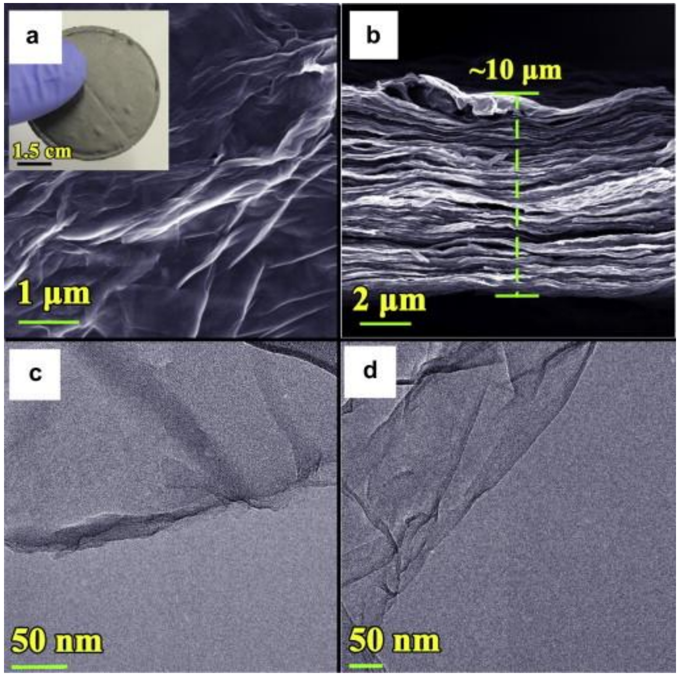


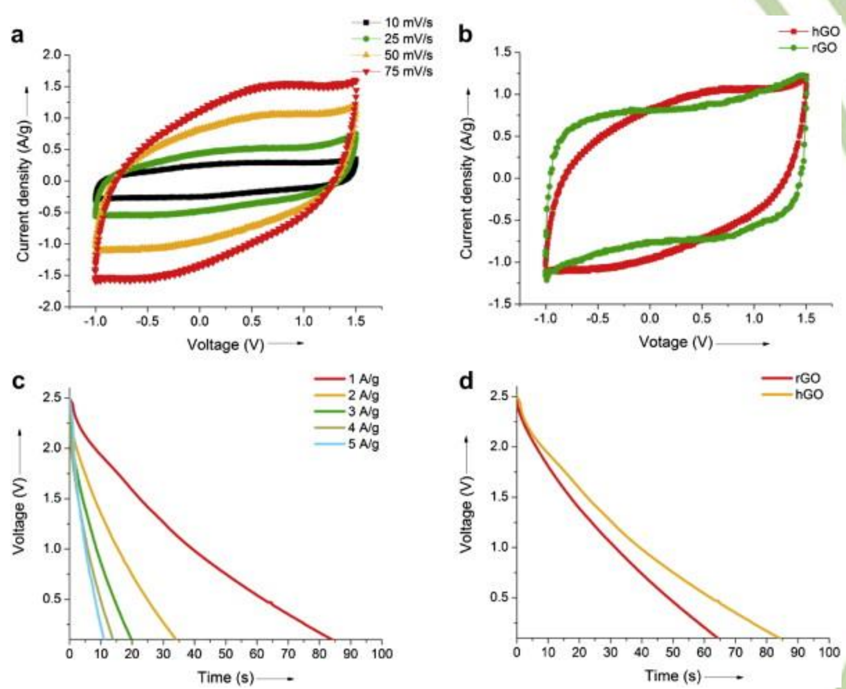


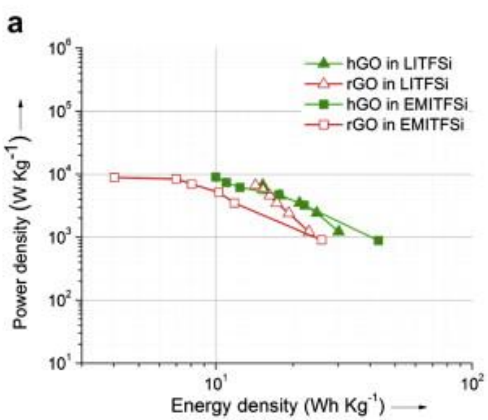


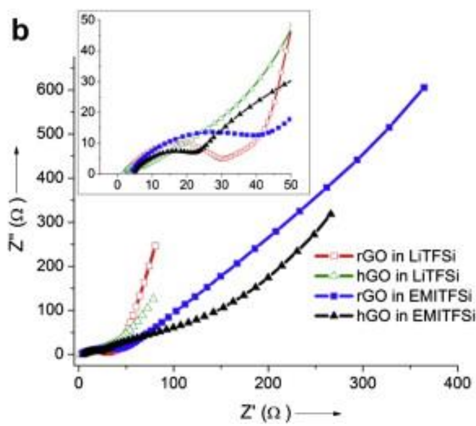
C – carboxylic
E – Easter
P - Purified

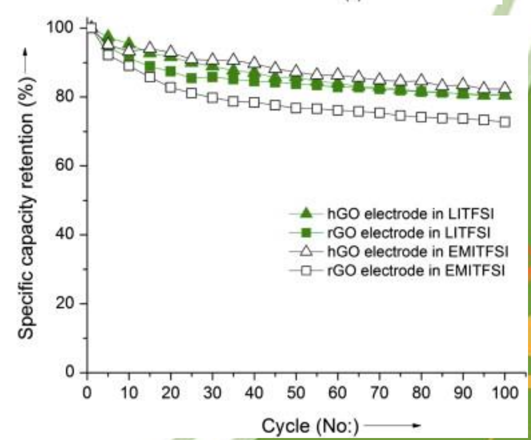
Graphene Nanosheet for EDLC



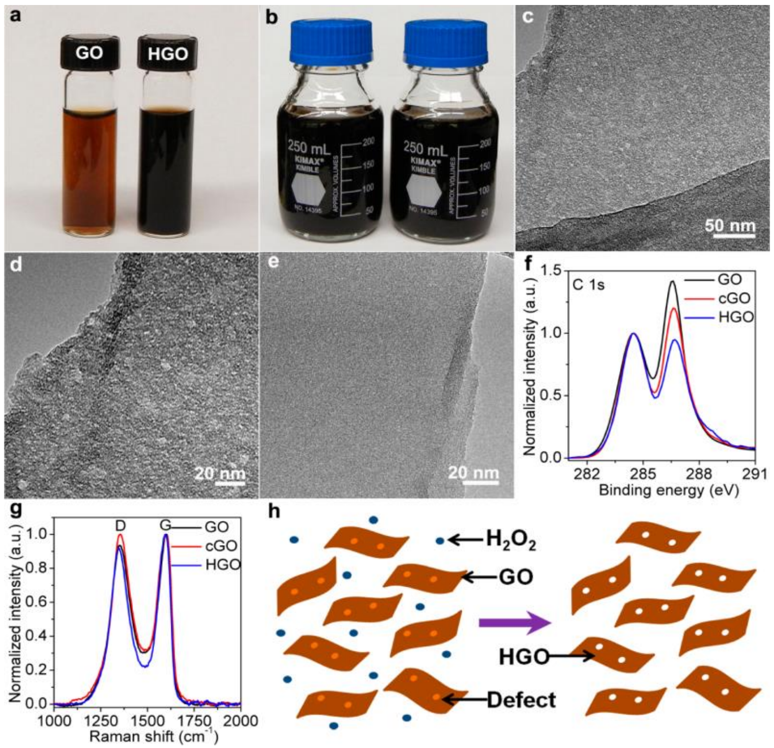


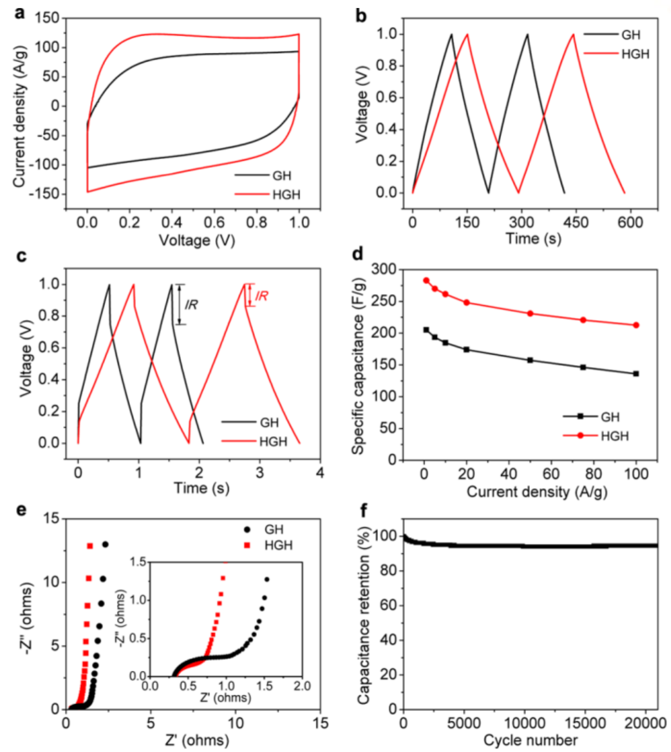






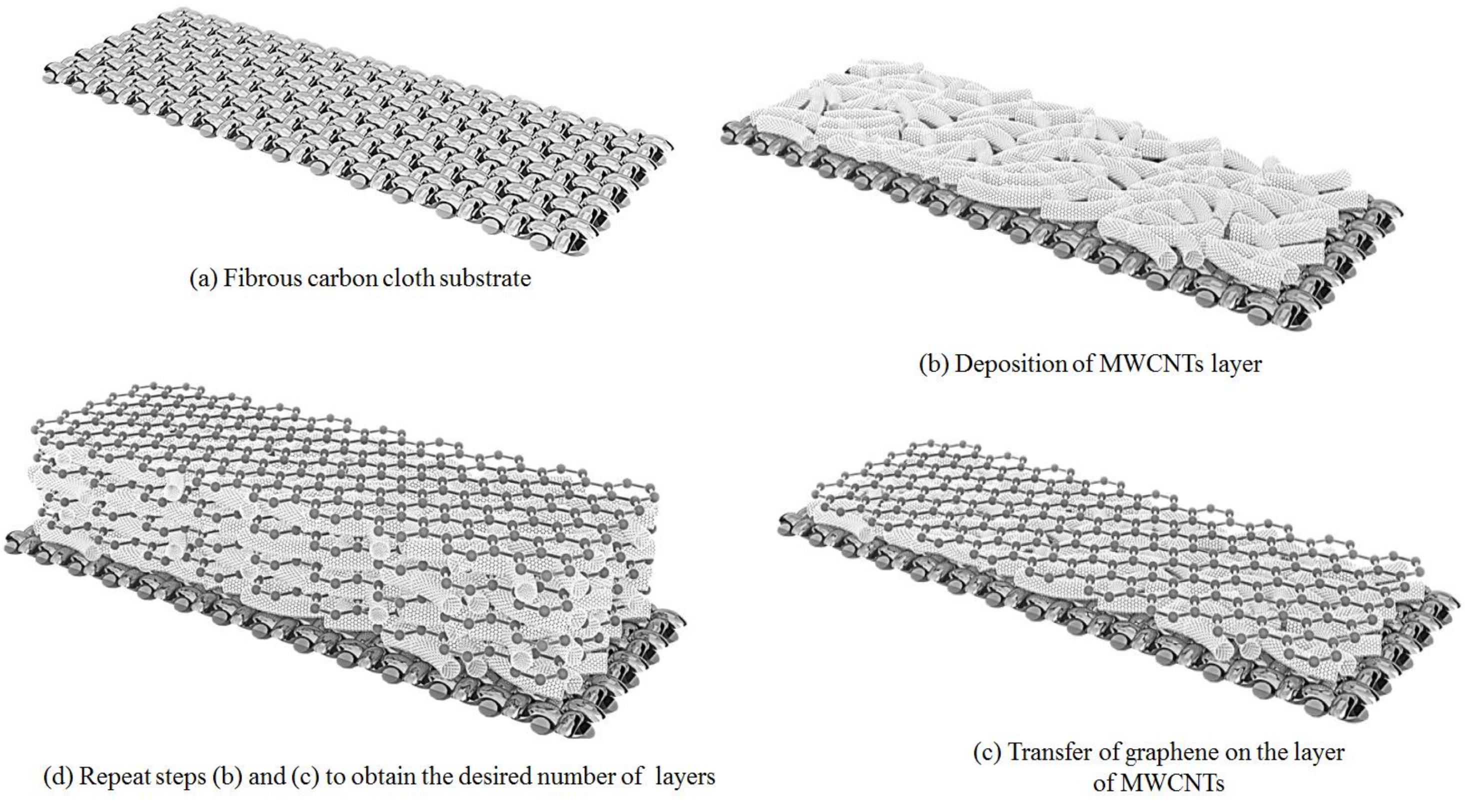
Solution Processable Holey Graphene Oxide





Nano letters 15 (7), 4605-4610

Graphene Sandwich between MWCNTs layers for Energy Storage Devices



(a) Fibrous carbon cloth substrate

(b) Deposition of MWCNTs layer

(c) Transfer of graphene on the layer of MWCNTs

(d) Repeat steps (b) and (c) to obtain the desired number of layers

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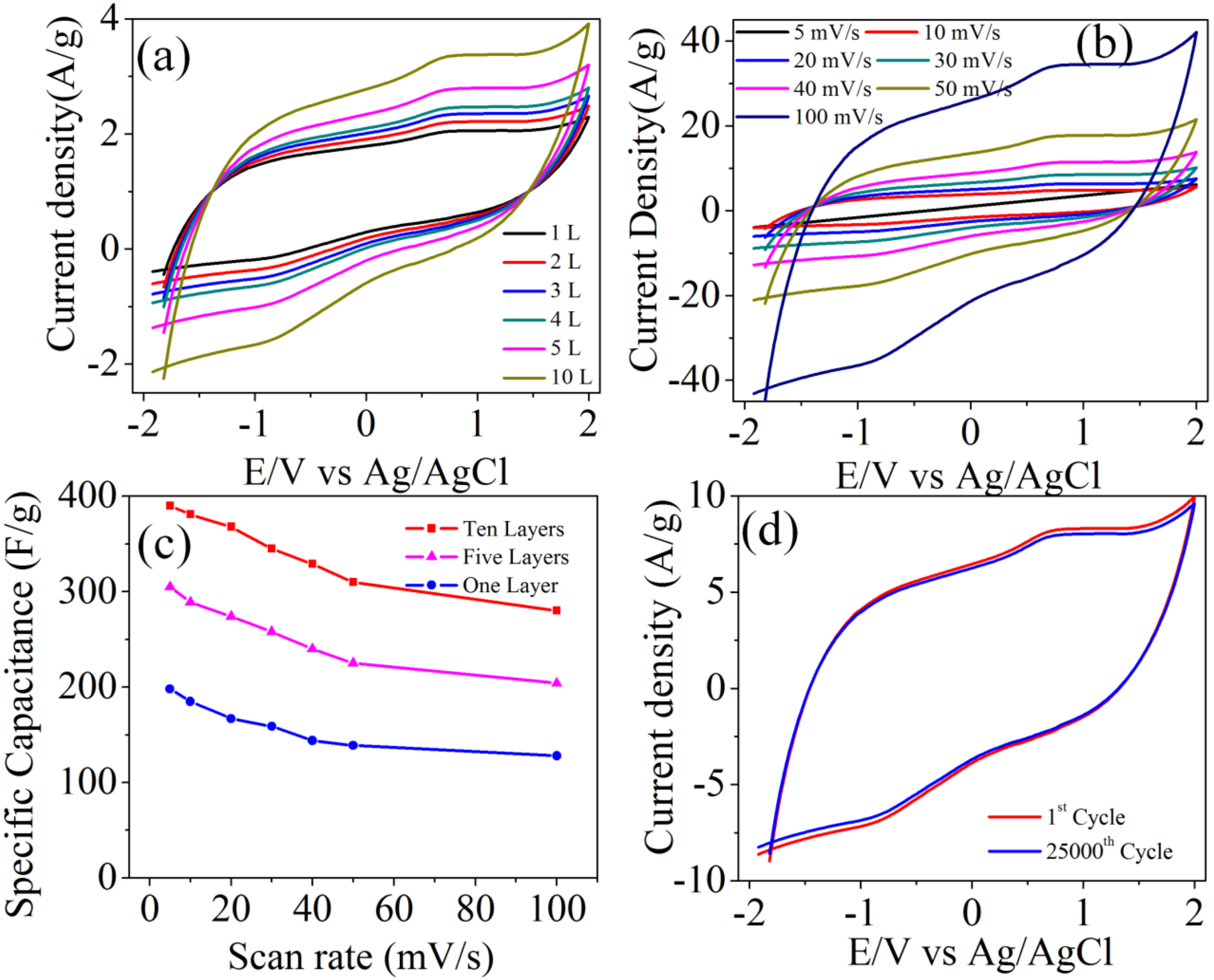
Graphene Sandwich between MWCNTs layers for Energy Storage Devices



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Pseudocapacitors

Store energy using fast surface redox reactions

Metal oxides:

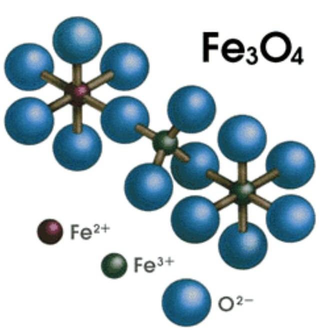
Capacity 1300 F/g (RuO_2)

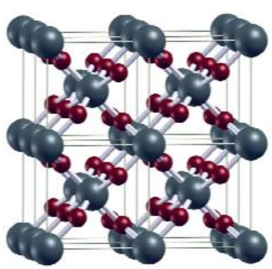
Nominal voltage 1.2 V

Conducting polymers:

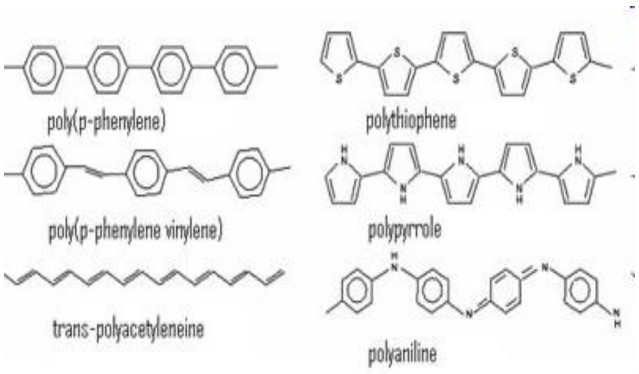
Capacity 30 – 40 mAh/g

Nominal voltage 1.0 V

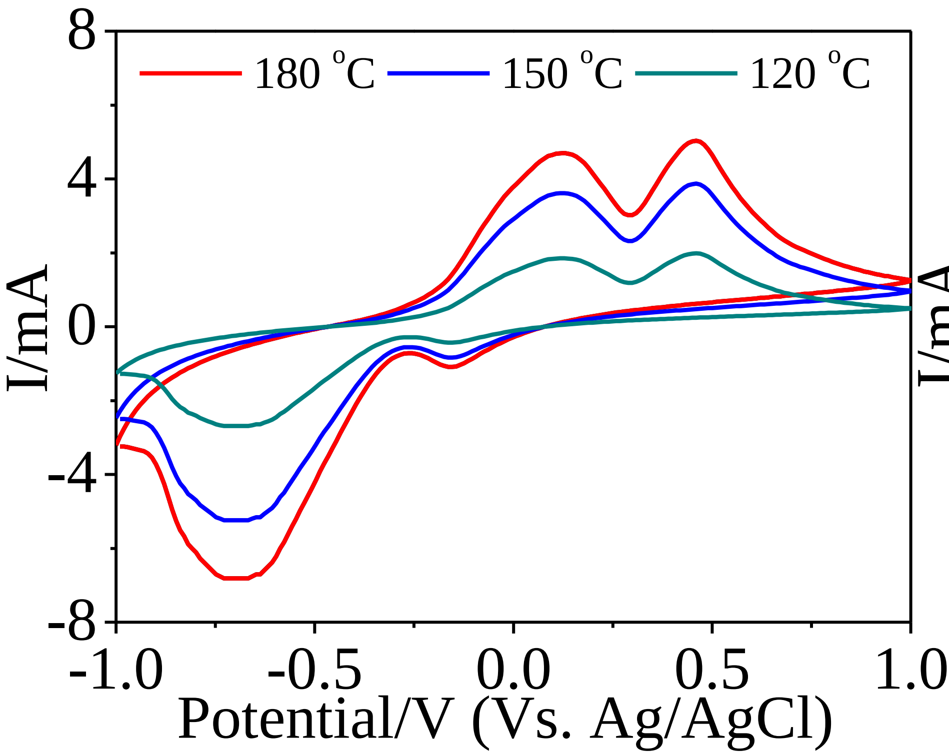


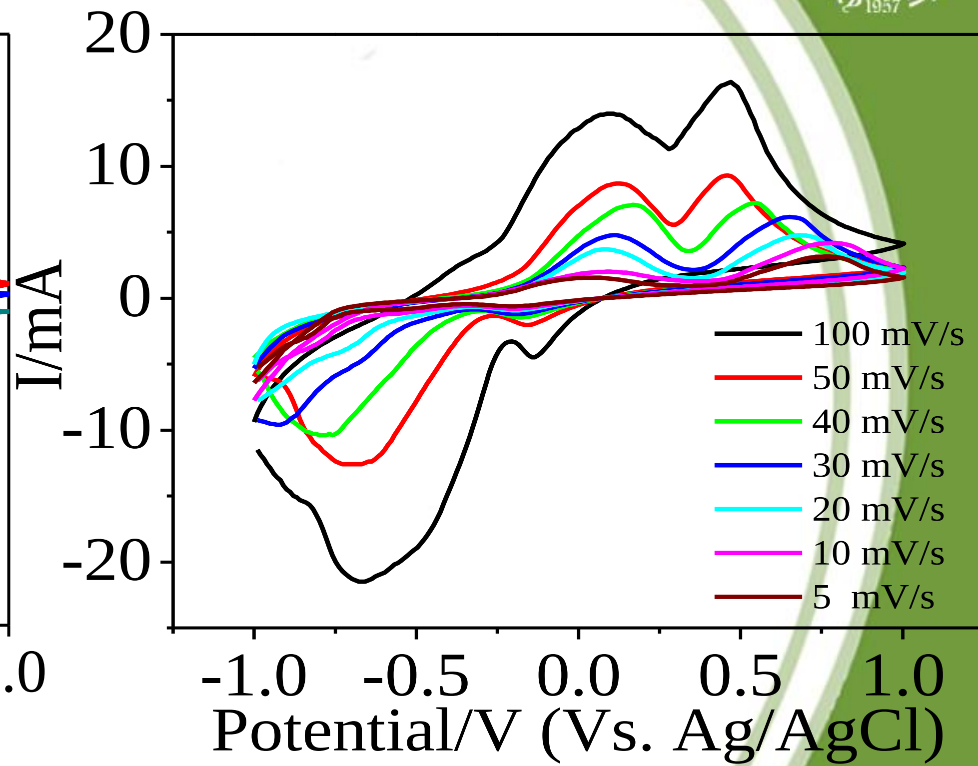


RuO_2



MoO$_3$ Nanorods for Energy Storage Applications





- Maximum current was obtained from the samples synthesized at 180 ^{0}C which was due to the increase of crystallinity and morphology.

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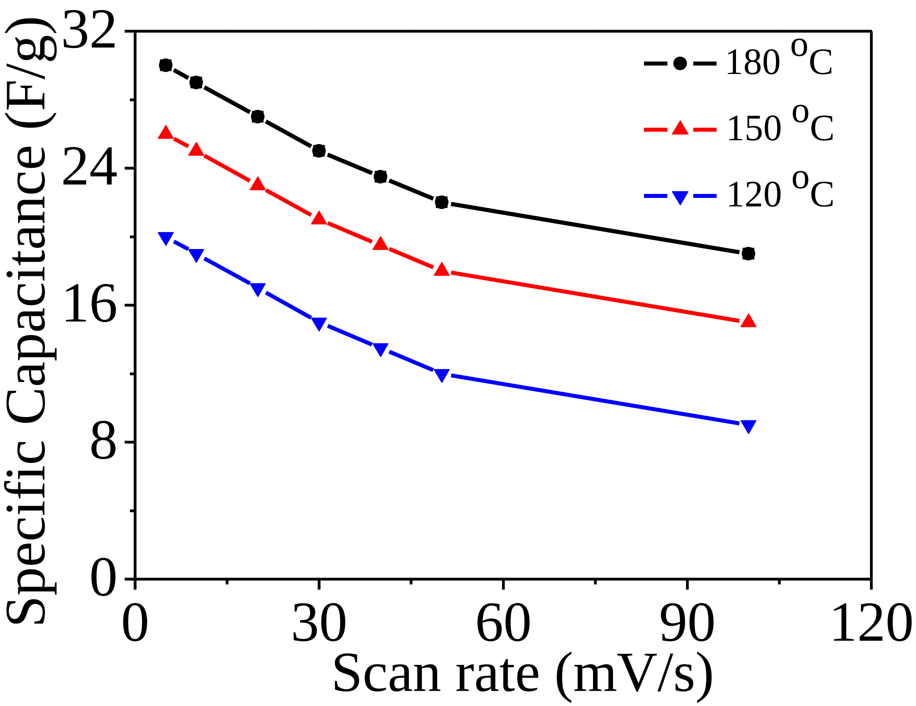
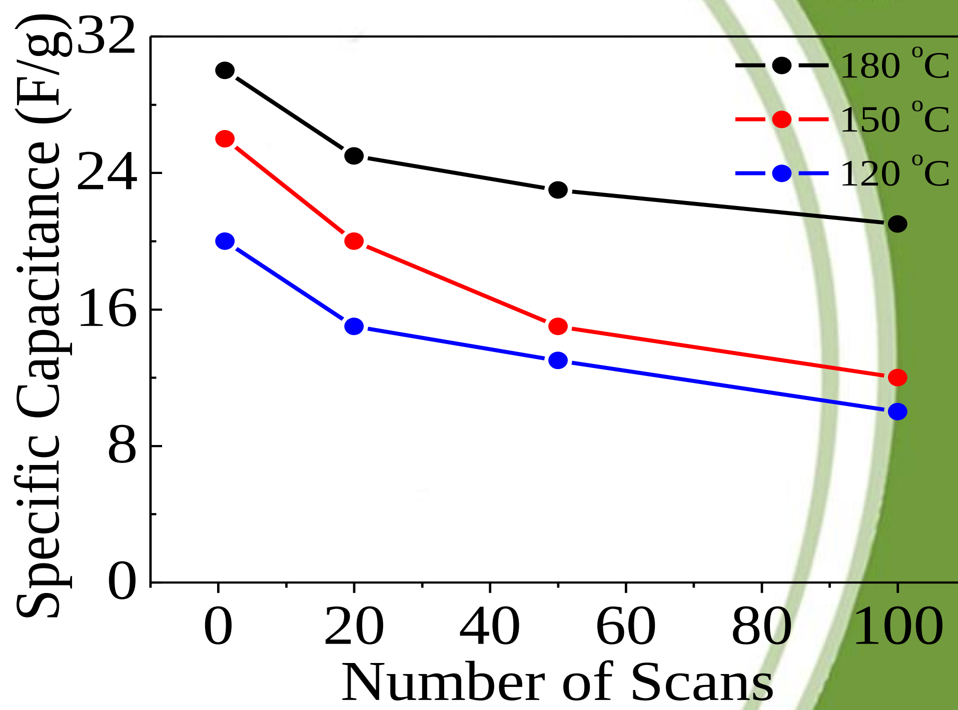
MoO_3 Nanorods for Energy Storage Applications





- The increase in ionic resistivity at higher scan rate leads to a drop in the capacitance of the nanorods.
- The specific capacitance of as synthesized nanorods at 180 °C was found to be higher than that of nanorods synthesized at 120 °C, and comparable to that of the 150 °C (at a scan rate of 5 mV/s).

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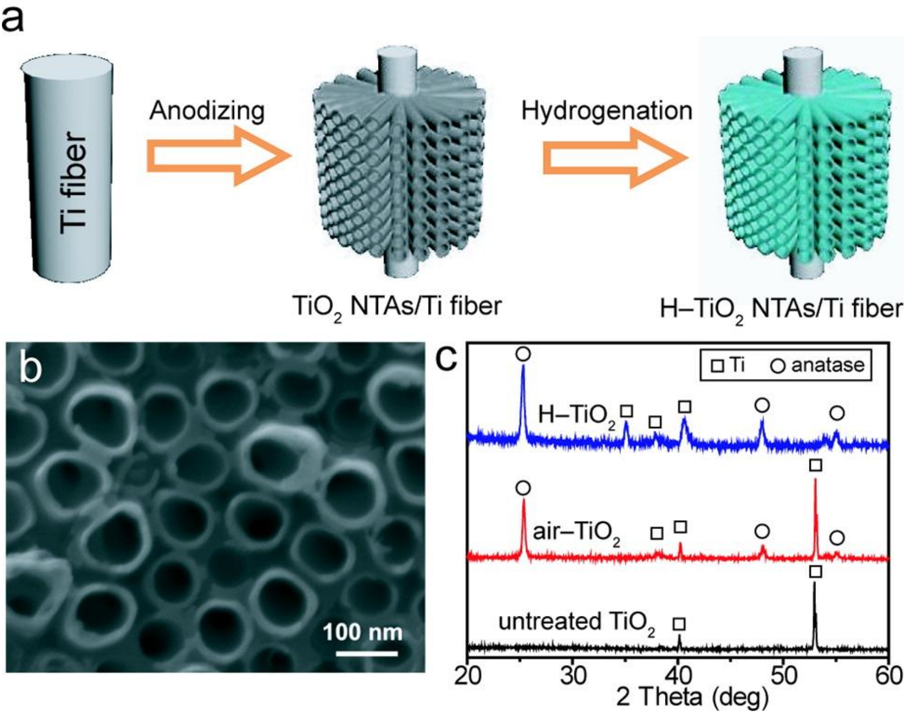
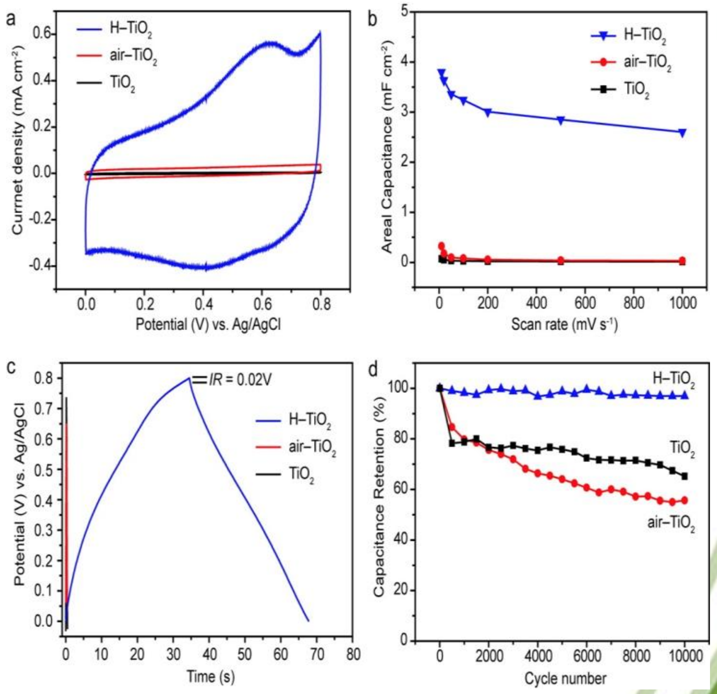
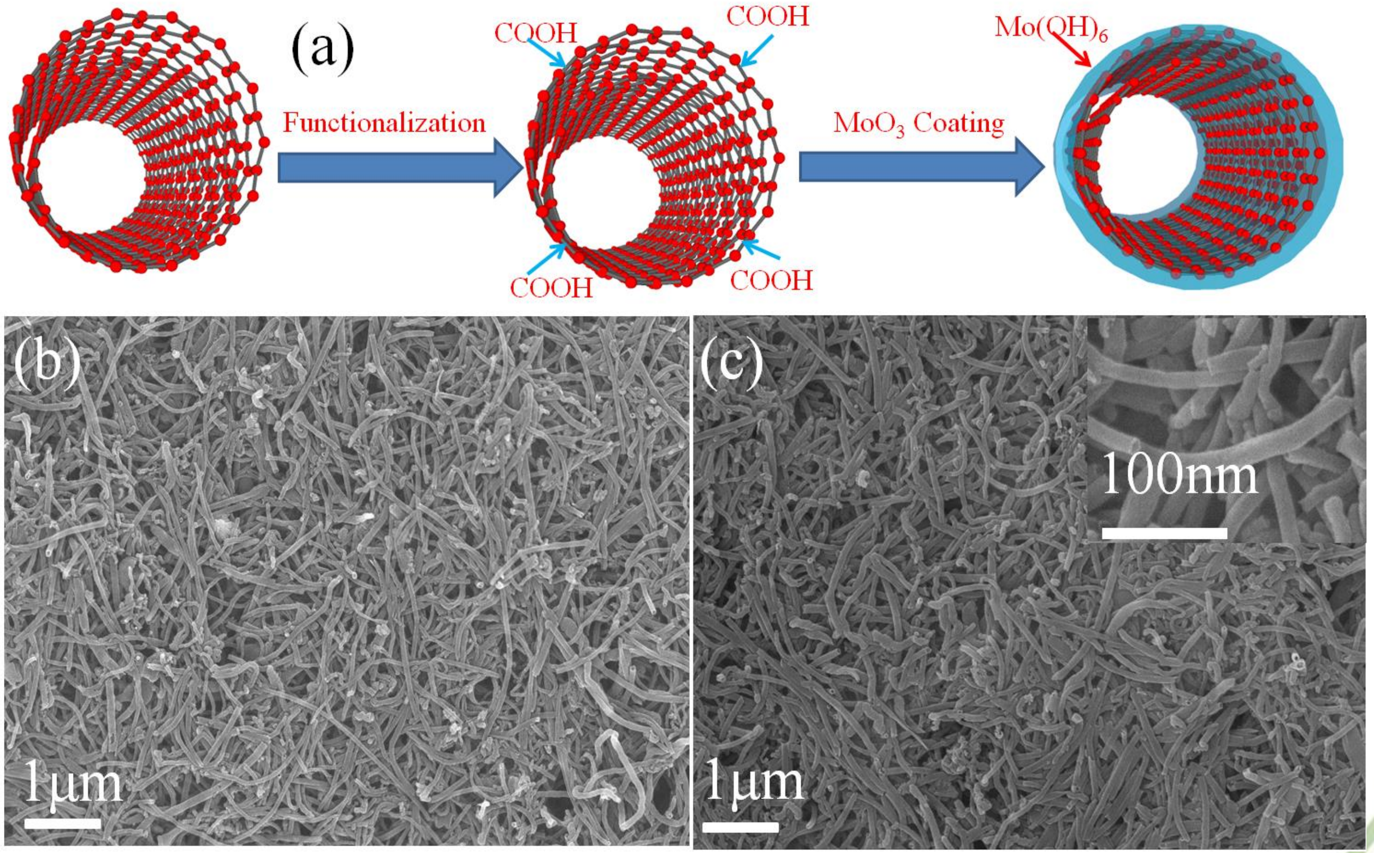
Hydrogenated TiO_2 as Supercapacitors





Ultra-thin Solution-based coating of Molybdenum Oxide on Multiwall Carbon Nanotubes



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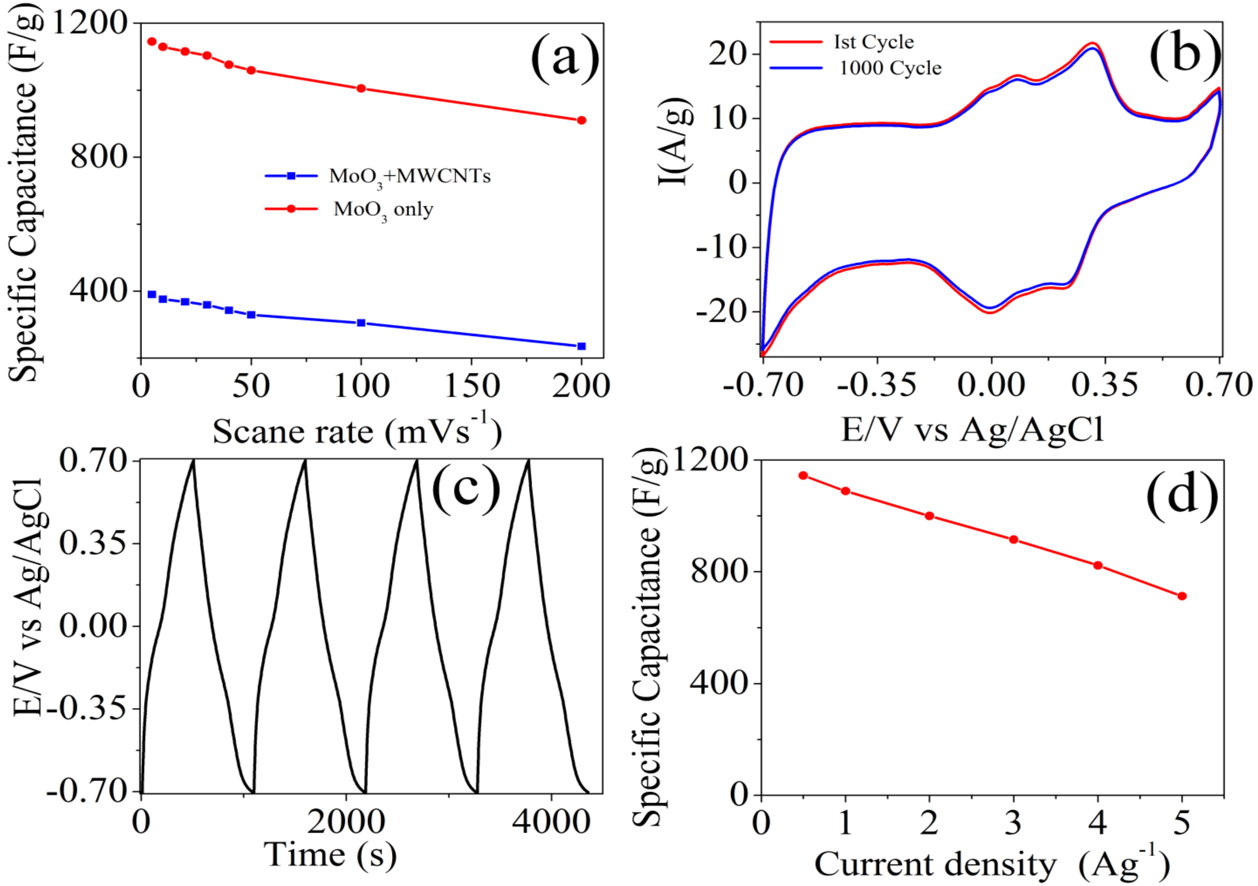

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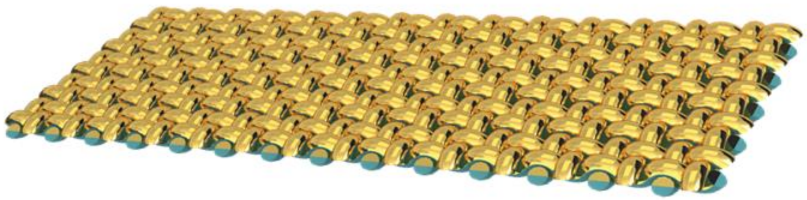
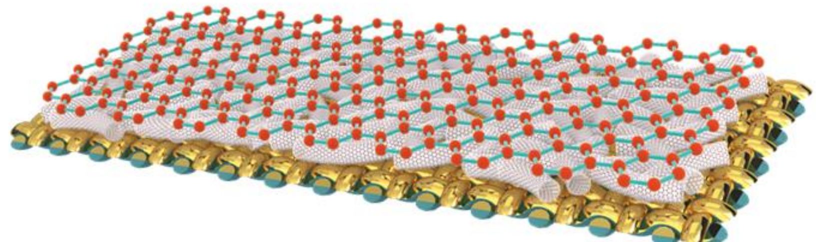
Ultrathin Metal Oxide Sandwich between Graphene layers for Energy Storage Devices

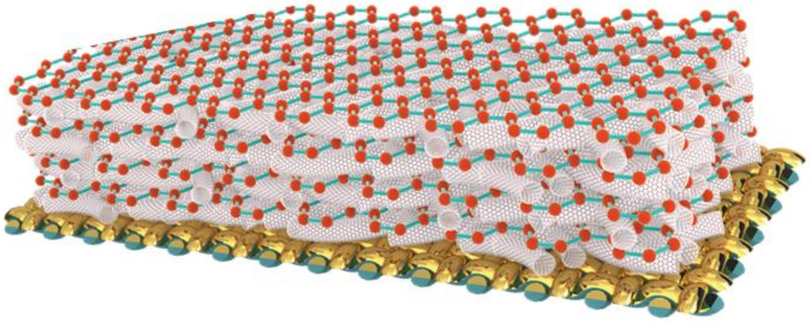


Ni/Cu/Ni/Au Coated Textile Fiber Substrate

Deposition of metal oxide coated MWCNTs layer



Transfer of Graphene on the Layer of metal oxide coated MWCNTs



Repeat the steps to obtain the desired number of layers

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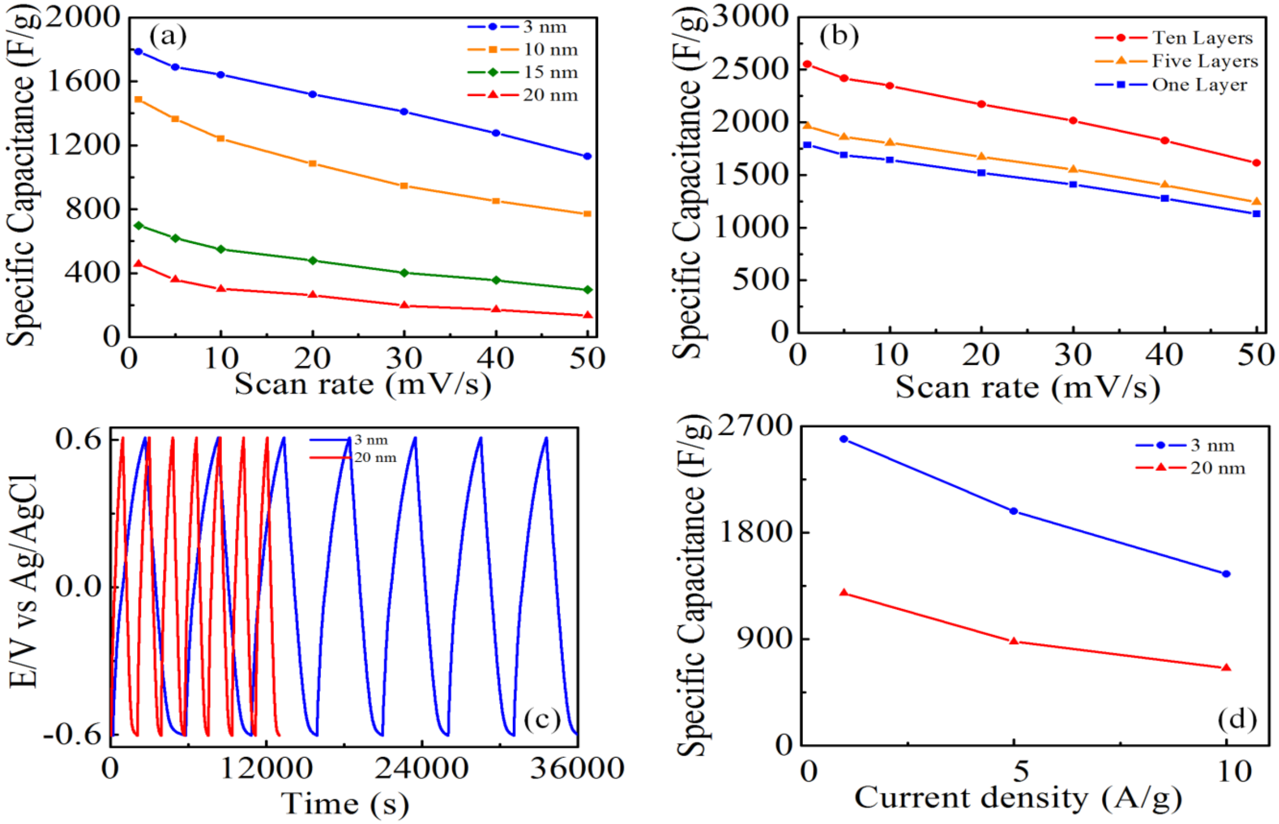
Ultrathin Metal Oxide Sandwich between Graphene layers for Energy Storage Devices



- The specific capacitance of metal oxide with thickness of 3 nm sandwich between graphene was found to be higher than that of higher thickness (2590F/g).

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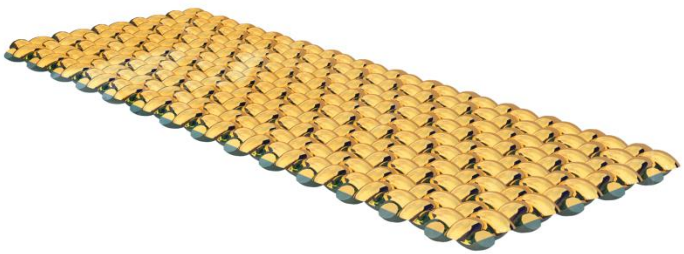
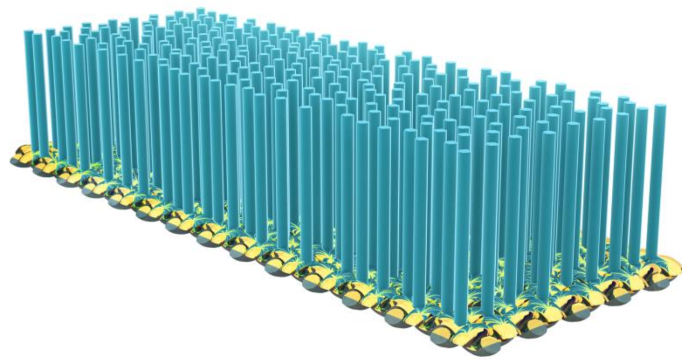
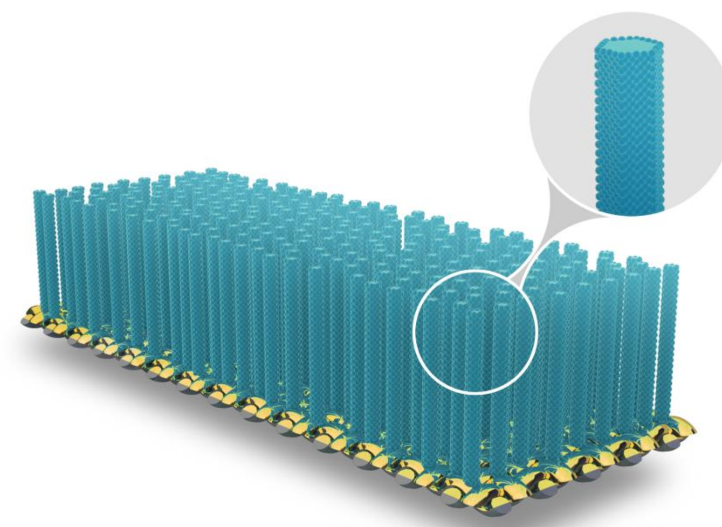
$Ni(OH)_2$-coated ZnO Nanowire-based Energy Storage Devices



Step 1: Preparation of Ni/Cu/Ni/Gold textile fiber

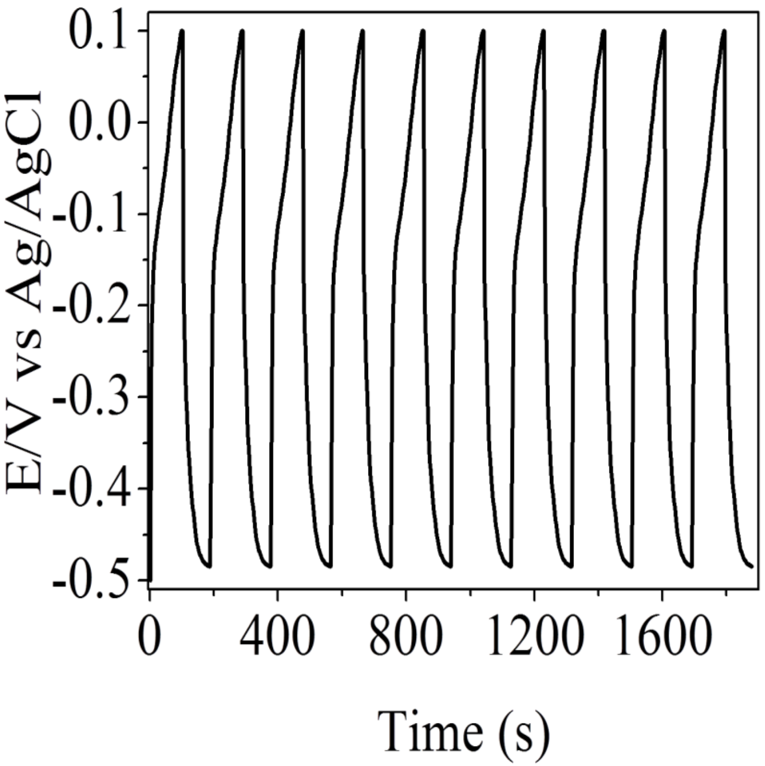


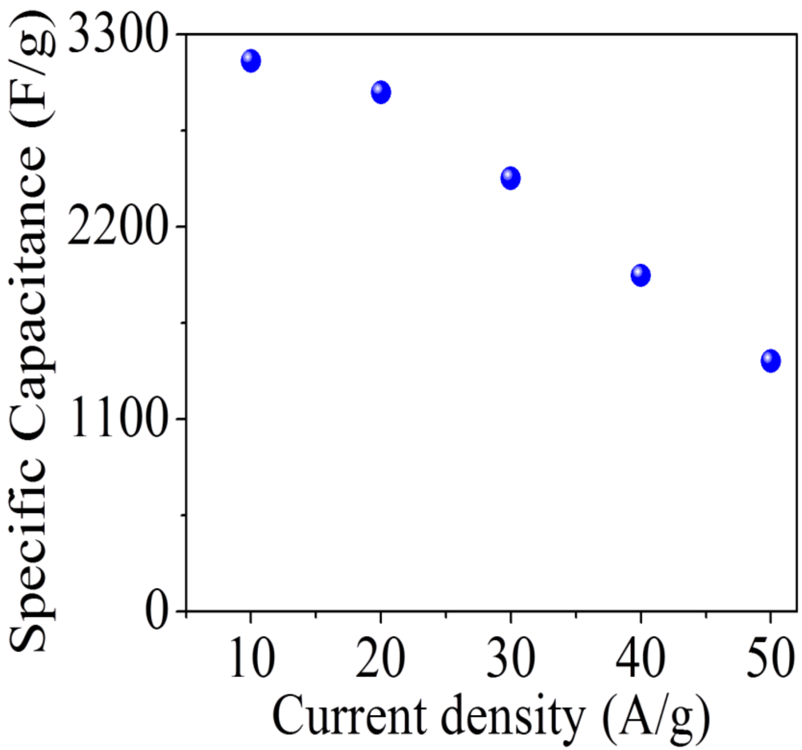
Step 2: Hydrothermal growth of ZnO nanowires



Step 3: Synthesis of $Ni(OH)_2$-coated ZnO nanowires

$Ni(OH)_2$-coated ZnO Nanowire-based Energy Storage Devices





- The $Ni(OH)_2$ coated ZnO nanowires electrodes show a nonlinear charge–discharge curve, which indicates electrode have pseudocapacitive behavior with a specific capacitance of 3200 F/g.

Materials for lithium Ion Battery

Design Considerations

1. Volumetric and/or gravimetric energy density
2. Cycle life
3. Safe operation
4. Energy losses in course of charge/discharge cycle
5. Power performance, needed for some applications
6. Environmentally friendly and inexpensive.

Materials Requirements

- Large reversible capacity reversible capacity
- Small irreversible capacity
- Desirable charge profile charge profile
- Desirable kinetics (rate capability)
- Long y g cycle and calendar life
- Ease of processing
- Safety
- Compatibility with electrolyte and binder systems
- Low cost

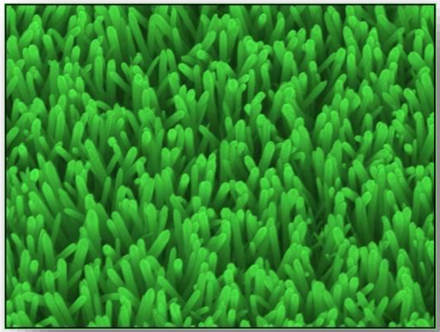
Major Types of Materials

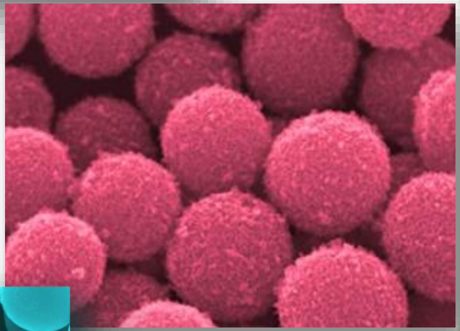
- Layered oxides with the α-$NaFeO_2$-type structure
- Oxides with a spinel structure
- Poly-anion oxides with the olivine and olivine-related structures

Anode Materials

1. Current Materials
    1. Carbonaceous
        1. Graphite
        2. Hard Carbon
        3. Soft Carbon
    2. Titanium Oxide
2. Future Materials
    1. Silicon
    2. Nanomaterials
    3. Other

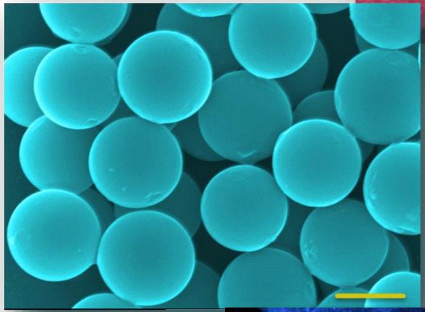
Structure and Designing Options

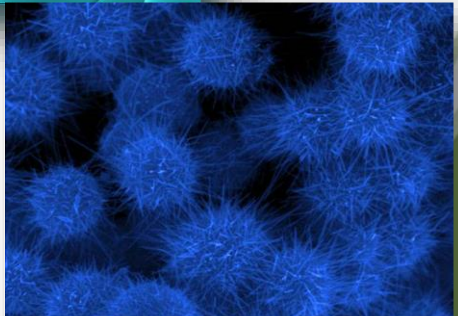




Some limitations such as:

1. Low electronic conductivity
2. Low ionic conductivity
3. Charge recombination
4. Wide band gap



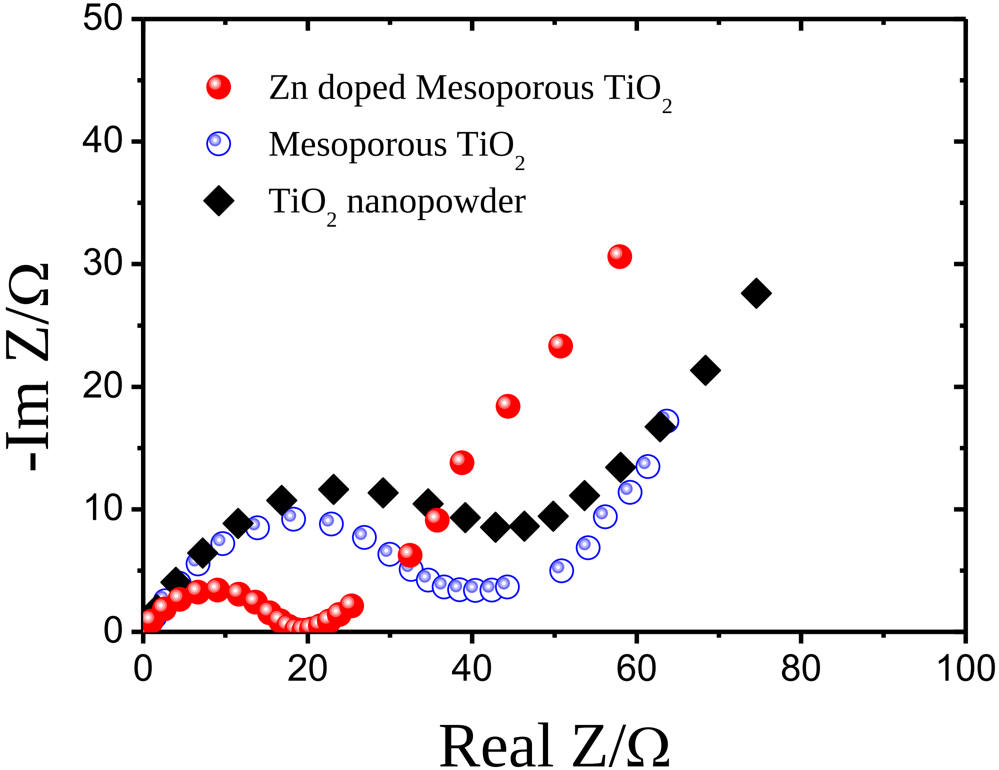


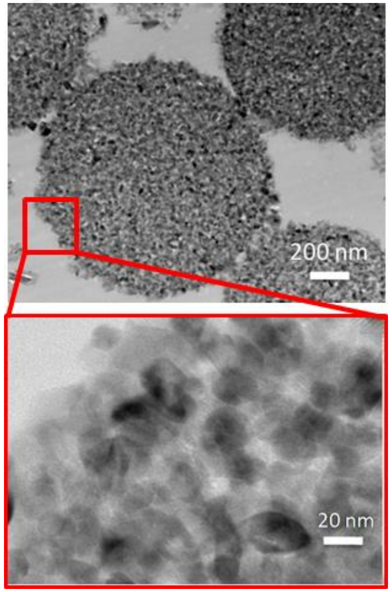
These limitations can be overcome by:

1. Tuning shape and size
2. Composite structures
3. Doping

Impedance Analysis

Zn Doped Mesoporous TiO_2 Microspheres

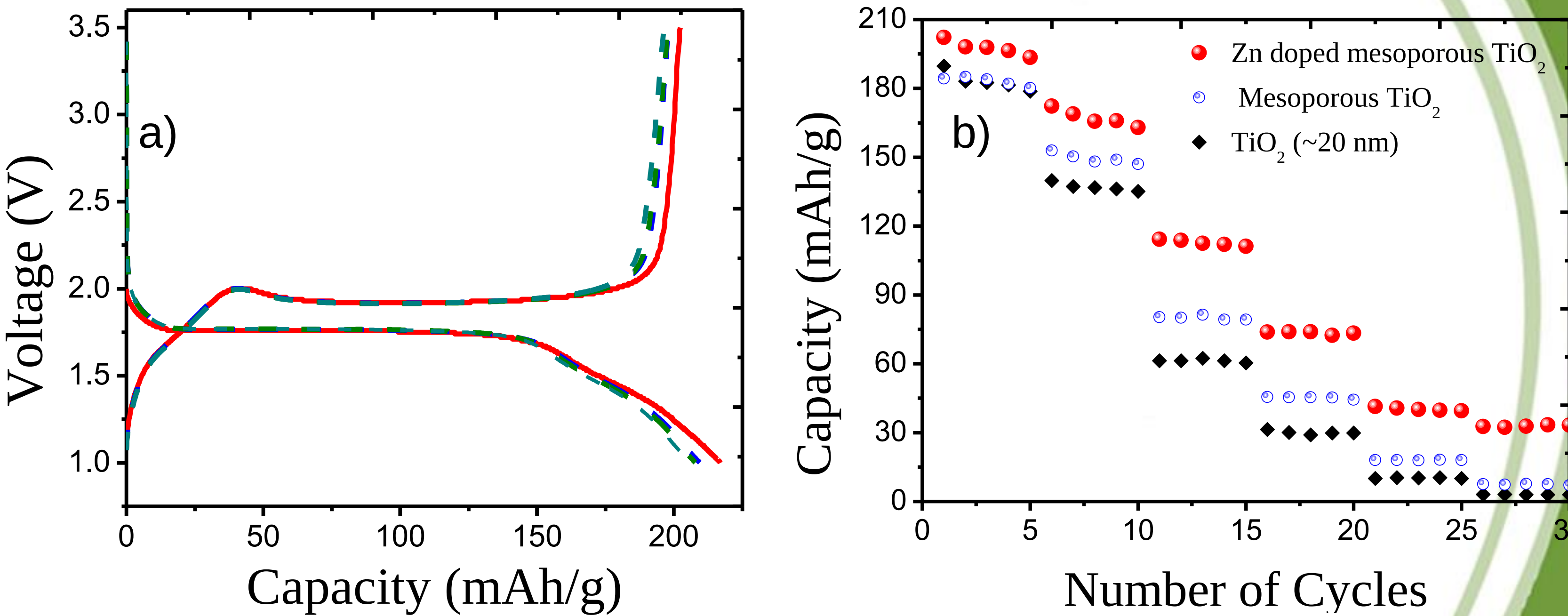




Nyquist plots for Zn doped mesoporous TiO_2 microspheres and 20 nm anatase TiO_2 nanopowder

Charge-Discharge Results

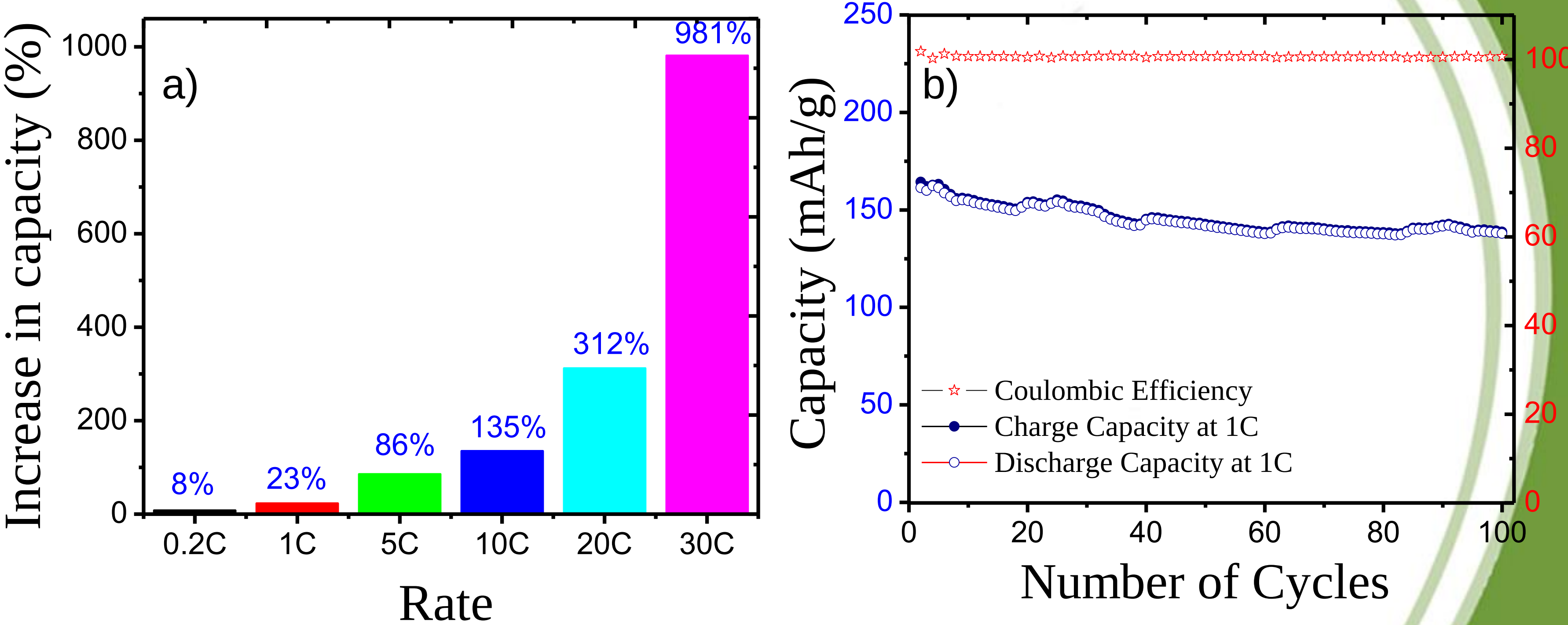
Zn Doped Mesoporous TiO_2 Microspheres



(a) Charge−discharge profiles for Zn doped mesoporous TiO_2 at C/5 charge−discharge rates. (b) Discharge capacity of Zn doped mesoporous TiO_2 and 20 nm anatase TiO_2 nanoparticles at different discharge rates

Charge-Discharge Results

Zn Doped Mesoporous TiO_2 Microspheres



(a) Percentage increase in discharge capacity of Zn doped mesoporous TiO_2 and 20 nm anatase TiO_2 nanoparticles at different discharge rates. (b) Cycling performance and Columbic efficiency of Zn doped mesoporous TiO_2 up to 100 cycles at 1C charge/discharge rates.

Thank you for your attention!