Supercapacitors

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Supercapacitors – in brief

Power Boost and Management Device: deliver the power measured in hundreds of kilowatts or megawatts

Energy Storage Device: when the high power is needed

AC line filtering: compact volume and on-chip applications

Enables:

Future technologies such as Smart energy systems; Smart grid; Internet of Thing;
Supercapacitors – in brief
Supercapacitors — in brief

\[ C = \frac{\varepsilon_r \varepsilon_0 A}{d} \quad E = \frac{1}{2} CV^2 \quad P = \frac{E}{t} - RI^2 \]

**Supercapacitor working principles:** A physical process for charges moving in and out, with atomic size of the \( d \) for charge separation to achieve extremely high capacitance, without any chemical reaction for very fast charging and discharging, and no material damage.

**Note:** The charge and discharge process in batteries is a slow process and can degrade the chemical compounds inside the battery over time. As a result, batteries have a low power density and short lifetime due to material damage.
Supercapacitors – in brief

Very famous Ragone Plot
Supercapacitors – comparing with battery

For Supercap: 5 to 7kwh/m^3 (Maxwell new - BCAP3000 P300 K04, and Aowei UCE15V50000)

http://www.epectec.com/batteries/cell-comparison.html
## Supercapacitors – comparing with battery

### Compare the supercapacitor with a typical Li-ion

<table>
<thead>
<tr>
<th>Function</th>
<th>Supercapacitor</th>
<th>Lithium-ion (general)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge time</td>
<td>1–10 seconds</td>
<td>10–60 minutes</td>
</tr>
<tr>
<td>Cycle life</td>
<td>1 million or 30,000h</td>
<td>500 and higher</td>
</tr>
<tr>
<td>Cell voltage</td>
<td>2.3 to 2.75V</td>
<td>3.6V nominal</td>
</tr>
<tr>
<td>Specific energy (Wh/kg)</td>
<td>5 (typical)</td>
<td>120–240</td>
</tr>
<tr>
<td>Specific power (W/kg)</td>
<td>Up to 10,000</td>
<td>1,000–3,000</td>
</tr>
<tr>
<td>Cost per kWh</td>
<td>$10,000 (typical)</td>
<td>$250–$1,000 (large system)</td>
</tr>
<tr>
<td>Service life (industrial)</td>
<td>10-15 years</td>
<td>5 to 10 years</td>
</tr>
<tr>
<td>Charge temperature</td>
<td>–40 to 65°C (–40 to 149°F)</td>
<td>0 to 45°C (32° to 113°F)</td>
</tr>
<tr>
<td>Discharge temperature</td>
<td>–40 to 65°C (–40 to 149°F)</td>
<td>–20 to 60°C (–4 to 140°F)</td>
</tr>
</tbody>
</table>

### Advantages and limitations

#### Advantages
- Virtually unlimited cycle life; High specific power; low resistance enables high load currents
- Charges in seconds; no end-of-charge termination required; Simple charging; draws only what it needs; not subject to overcharge
- Safe; forgiving if abused
- Excellent low-temperature performance

#### Limitations
- Low specific energy; Linear discharge voltage prevents using the full energy spectrum
- High self-discharge; higher than most batteries
- Low cell voltage; High cost per watt

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Source: Maxwell Technologies, Inc
Supercapacitors – Challenges

Energy Density improvement (for both EDLC and PsC)

• Micro/nano fabrication: Scaffold with great surface gain, and controllable configuration for one dimension ion diffusion.

• Nanocomposite materials: Electrochemical active material with Meso/Nano porous for low distributed resistance in series.

• Electrochemical material systems for high operation voltage and long term stability.
Supercapacitors – Application for energy storage

Pure-play battery or hybrid grid energy storage?

1. Energy storage enables the *decoupling* of electricity generation from demand.
2. Renewable energy sources are subject to significant variability, both in a few seconds, and in hourly, daily or seasonal.
3. Batteries are used in the *energy-only* needs of the grid. But battery technology often do not offer all of the energy and power capacity that is needed for the integrity of Transmission and distribution grid operation.
4. Supercapacitors and Battery *hybrid* system is only solution to meet the needs of both the energy and power grid.
5. Utility Duke Energy’s battery-superacapacitor system In North America leverages supercapacitors to perform solar smoothing tasks at the distribution level in **real time** – particularly when the solar power on the grid fluctuates due to cloud cover, atmospheric conditions or as unforeseen PV array and system circumstances may
6. The hybrid technology directly addresses milliseconds to seconds high power and **fast response** applications, as well as **hours-long energy capacity** applications.

System Integrator: Win Inertia. 
Image: Maxwell Technologies.
Supercapacitors – Application for Smart Grid
Supercapacitors — Application for Smart Grid

ABB offers distributed energy storage modules for grid storage purposes, such as peak shaving, load shifting, voltage regulation, renewable integration, and backup power.

Maxwell Supercapacitors for Power Stabilization:
Yangshan Deep Water Port

ISSUE
Located near Shanghai, Yangshan Deep Water Port’s 23 quay cranes have enough power draw to cause significant voltage fluctuations on the local grid for 10 to 15 seconds at a time. The port is located at the end of a 20-mile bridge, and increasing the transmission line capacity was deemed too costly.
Supercapacitors — Application for large mass electrical vehicles

Large Mass Electrical Vehicles

Stop-and-Go driving mode
Large Power Starting

Maxwell Supercapacitors for Wayside Energy Efficiency and Frequency Regulation:

Brake-Energy-Recovery

Southeastern Pennsylvania Transportation Authority Light Rail System
Supercapacitors — Application for Power demand boost

Reduce 20% motor capacitance – cost efficiency
Reduce 30% fuel consumption – working efficiency
Energy recovery – improved energy efficiency

Image Source: Fisker

Word First Hybrid Race Car: Powered by Supercapacitors
The too-good-for-this-world 2.0 liter V10 hybrid Connaught

Fisker’s Emotion: Powered by Supercapacitors
400 mile (640km), and charges in just 9 minutes
Tesla competitor—Tesla S 100PD, 100kwh
335 miles (539 km), and charges in hours
Supercapacitors — Application for Smart home

Supply:
Wind – Solar - local grid

Consumption:
Heating – Kitchen Electronics - Electrical Cars - Lighting – IoT at home

Smart energy system demands:
Load shift for energy generation and consumption & Power boost for same-time multi-applications
Supercapacitors — Application for IoT and smart clothes

Demands: flexible cordless power

Approach: Harvester and Storage Integration
Supercapacitors – What we do in USN

Earlier work: 3D MEMS SuperCaps based on Silicon

LiClO$_4$/H$_2$O/PVA

“Interdigital structure for SuperCap” - first published by our group, now become popular configuration.

- W Sun, X Chen / Microelectronic engineering 86 (2009) 1307-1310
- W Sun, X Chen / Journal of Power Sources 193 (2009) 924–929
Supercapacitors – What we do in USN

Earlier work: 3D MEMS SuperCaps based on Silicon

Planar interdigital electrode supercapacitor ...... was first introduced by Wei Sun and Xuyuan Chen, having the advantage of high charging capacity due to its interdigital structure. ......

Cited by 262, including
- Nature nanotechnology, IF 38.986
- Chemical Society Reviews, IF 38.618
- Energy & environmental science, IF 29.518
- Advanced Energy Materials, IF 16.721
- Advanced functional materials, IF 12.124
- Nano Energy, IF 12.343
- Angewandte Chemie, IF 11.994
- Small, IF 8.643
- Nanoscale, IF 7.367
- Journal of Power Sources, IF 6.395
- Carbon, IF 6.337


Chapter 8: Interdigitated MEMS Supercapacitor for Powering Heart Pacemaker
research-article
Hafzaliza Erny Zainal Abidin, Azrul Azlan Hamzah*, Jumril Yunas, Mohd Ambri Mohamed and Burhanuddin Yeop Majlis
Supercapacitors — What we do in USN

Earlier work: 3D MEMS Supercap by LIGA-like technology

Capacitance density of 0.029 Fcm\(^{-2}\)

Cited by Nature Nanotechnology 2014, IF 38.986

Wei Sun and Xuyuan Chen, Microelectronic engineering, Volume 86, Issues 4-6, April-June 2009, Pages 1307-1310
Supercapacitors — What we do in USN

Earlier work: 3D MEMS SuperCaps by DRIE technology

Capacitance density of 0.056 Fcm⁻² (world record)

Cited by Chemical Society Reviews 2016, IF 38.618

Supercapacitors — What we do in USN

Recent work: Micro/Nano scaffold Si-grass
Supercapacitors — What we do in USN

Recent work: Micro/Nano scaffold Si-grass+CNT(top)/Graphene(bottom)
Supercapacitors – What we do in USN

Recent work: Micro/Nano scaffold Si-grass+graphene

Graphene forest active material – first seen graphene configuration
Supercapacitors – What we do in USN

Recent work: Micro/Nano scaffold TiO$_2$ Nanotube + grass
Supercapacitors — What we do in USN

TiO$_2$ nanotube scaffold with TiN layer

TEM picture of TiO$_2$ + TiN nanotube
Supercapacitors — What we do in USN

Recent work: Micro/Nano scaffold Nickel foam + carbon

Nickel foam scaffold

Nickel foam scaffold loaded with carbon material by microfabrication
Supercapacitors — What we do in USN

Recent work: Micro/Nano scaffold FeO+CrO+NiO

Anodic etching at 12°C  Anodic etching at 17°C
Supercapacitors – What we do in USN

Si-grass/TiN EDLCap
Supercapacitors — What we do in USN

Si-grass/TiN/MnO PSCap
Supercapacitors – What we do in USN

Si-grass/CNT EDLCap

Cell performance normalized to one electrode
Supercapacitors — What we do in USN

Si-grass/CNT/MnO₂ PSCap

Cell performance normalized to one electrode
Supercapacitors — What we do in USN

TNT/reduced layer PSCap

(a) Ethanol Ethanol volatilize Annealing (I) (II) (III) Ti foil (b) Nano grass TNTs Ti foil 0.5M Na2SO4 SU-8 Stripping time increasing

- (a) Graphs showing current density vs. potential for different samples.
- (b) Controlling current density at various scan rates.
Supercapacitors — What we achieved at USN

1. In plane interdigital supercapacitor configuration

2. 3 Patents applications

3. More than 20 papers in Journals and Conferences
   Taper Silicon Nano-Scaffold Regulated Compact Integration of 1D Nanocarbons for Improved On-Chip Supercapacitor,
   Pai Lu, Lutz Müller, Martin Hoffmann, Xuyuan Chen

   *Nano Energy, 41 (2017) 618. IF 12.343*
   One of the highest Impact Factor research paper from IMS.

4. PhD graduated, 1 PhD defence scheduled, 3 PhD newly enrolled,