Multifunctional Electronics

Flexible and transparent smart phone, flexible computer, Flexible electronic newspaper (Wearable Electronics)

Devices require mechanically flexible, functional, and high performance energy storage systems

Electrode Materials
- 3D Nanostructures
- Electro-Mechanical Stability
- Optical Transparency etc.
SP² Carbon Nanostructured Materials

- **Mechanical Properties**
  - Strong sp² Carbon-Carbon covalent bonding
  - High elastic modulus (1 TPa) and High strength

- **Electrical and Optical Properties**
  - High Mobility
  - Highly conductive w/wo mechanical deformation
  - High current density ($10^9$ A/cm²)
  - Optically Transparent

- **In-plane Properties of Graphitic Carbon**
  - Good thermal conductivity (<3000W/mK)
  - Good chemical stability
Engineering SP2 Nanostructure

**Limitation of current CNT/graphene based networks**

- Built on weak van der Waals interactions between CNTs, CNTs-Graphene
- Lower mechanical strength, electrical and thermal conductivities due to a lower pulling resistance, electron and phonon scatterings at these “unconnected” junctions

*Transforming physical Junctions into covalently bonded sp² Chemical Junctions*

Terrones, Ajayan et al., PRL, 2002

J. Tour et al., Nature Communications, 2012
Restructuring $sp^2$ Lattice and Network Structure

A voltage-induced electrical fusion of SWCNTs

H. Jung et al, Nature Communications, 2014
Restructuring \( sp^2 \) Lattice Structure

Engineering SP2 Nanostructure

(a) Graph showing resistance (kΩ) vs. cycles with data points at 0.4V_b, 0.6V_b, and 0.8V_b.

(b) Graph showing V_A/V_A^0 vs. V_a (V_b units) for pristine samples and after 3000 cycles.

(c) Graph showing resistance drop (%R) vs. source on time (msec.) with data points at 0.8V_b.

(d) Graph showing normalized resistance change vs. V_a (V_b units) with data points at 0.4V_b, 0.6V_b, and 0.8V_b.

(e) Graph showing thermal conductivity (W/mK) vs. energy loss (eV) with data points labeled σ*(C-C) and π*(C=C) and intensity (a.u.) vs. energy loss (eV) with an arrow indicating a peak.
Engineering Nanostructure and Morphology

Pristine CNT fiber
Thermal Conductivity 15W/mK

Fused CNT fiber
Thermal Conductivity 110-130W/mK

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J. Hao et al, Unpublished

Jung's Research Group
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Engineering Nanostructure and Morphology
Engineering Nanostructure and Morphology

[Images of nanostructures and graphs showing intensity vs. 2θ (degree) for original fiber and fused fiber in different conditions.]
Carbon Nanocups

Graphitic nanostructures having smaller length/diameter (L/D) aspect ratio, *nanoscale cup morphology*, can effectively contain other nanomaterials and polymers, leading to multi-component hybrid nanostructures.

Multifunctional Nanosystems

- Energy Storage
- Nanogram Quantity Container
- Multifunctional Sensors
Engineering 3D Nanoscale Architecture

**Fabrication Process**

The length of nanochannels are controlled by second anodizing time.

- Thermal CVD of Carbon

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H. Jung et al. Scientific Reports (2011)
3D Carbon Nanostructured Film for Supercapacitor Electrodes

- Electrically Conductive: Surface Conductivity: 117 S/m
- High surface area and highly disordered graphitic layers provides the effective permeation of the polymer electrolyte and their conformal packaging with electrodes.
- Unique nanoscale cup feature enables the easy access and faster transport of ions at the electrode/electrolyte interface resulting in higher power capability.
- High current carrying capability, substantial mechanical strength, and small effective electrode thickness (5-10 nm: \textit{80-85\% Transmittance at 550nm wavelength}) allow us to build \textit{optically transparent} and \textit{mechanically flexible} reliable thin-film (solid state) energy storage devices.
Flexible and Transparent Supercapacitors

- CNC films: Outer graphene layers are acting as current collectors and the innermost layer exposed electrolyte is acting as an electrode.
- Polymer electrolyte (PVA-H₃PO₄) is acting as both electrolyte and separator.

(a) concave and (b, c) convex and (d-f) branched nanocup films (H. Jung et al. Scientific Reports 2012)
Flexible and Transparent Supercapacitors

(a) Cyclic voltammetry (CV) measured with 10 – 500 mVs\(^{-1}\) scan rates. (b) Galvanostatic charge/discharge (CD) results measured at a constant current density of 5 µAcm\(^{-2}\). The capacitances by the geometrical area calculated from CD curves are 409 µF cm\(^{-2}\). (c) The capacitance change as a function of temperature.
Flexible and Transparent Supercapacitors

Normalized capacitance as a function of cycle-number (10,000) and w/wo the mechanical deformation (45° bending).

(Jung, Ajayan et al. Scientific Reports 2012)

Normalized capacitance as a function of cycle-number (10,000) and w/wo the mechanical deformation (45° bending).

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