Capacitive Storage for Wind Energy Generated by Piezoelectric Polymer Materials

Bin Chen

Department of Electrical Engineering
University of California, Santa Cruz, CA

Advanced Studies Laboratories
NASA Ames Research Center, Moffett Field, CA

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Introductions

Distributed Energy Storage for Sustainable Energy

- Loading shift and peak power generation
  - power generation and capacity
- Cycling life and safety tolerance

...the theoretical specific energy of a lithium thionyl chloride battery is 1420 Wh/L, comparable to the theoretical specific energy of TNT at 1920 Wh/L.

Micro-grid Energy Storage for Transportation

- Energy density and power density
  - 60 mile vs. 30 mile
  - Li battery (200 Wh/kg) for 10,000–20,000 Wh for EV and PHEV
- Cycling response and operating temperature
  - -30 to 52 °C

Materials Challenges

- Cost of materials synthesis for electrodes and electrolytes
- Performance response to temperature

Electrical Energy Storage – EES Devices

Rechargeable Batteries

Electrochemical cell that stores energy in a complex system

$$E=-G/nF - (RT/nF)\ln(a_{product}/a_{reactant})$$

Electron and ion transports, activation barrier, impedance of the ***electrode interface***

Redox Flow Cells and Fuel Cells

Two parallel electrodes separated by an in exchange membrane, forming two electrolyte compartments storing electrical energy.

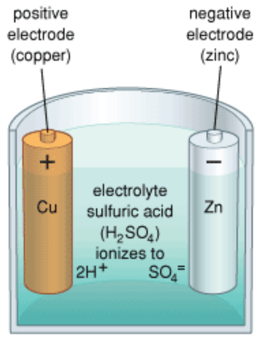
The electrolyte solutions charge and discharge at electrodes to generate current.

Electrochemical Capacitors (EC) or Supercapacitors, Ultracapacitors

High specific and volumetric capacitances results from high internal surface area of nanporous carbon electrode and nanosize thickness of double layers

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

Batteries: Chemical Energy Storage



Rechargeable batteries

Lead-acid, Nickel, Sodium beta, ***Lithium***

cost, , operating temperature range, volumetric energy density, cycling stability

Materials design needs in the complex system

Cell Voltage and charge storage

crystalline and amorphous solids, polymers, aqueous and organic liquids

active and passive components

Volume and structural changes of active sites at electrodes

heterogeneous electronic structures with boundary conditions

Electrochemical processes

charge transfer, charge carrier and mass transport and phase transition

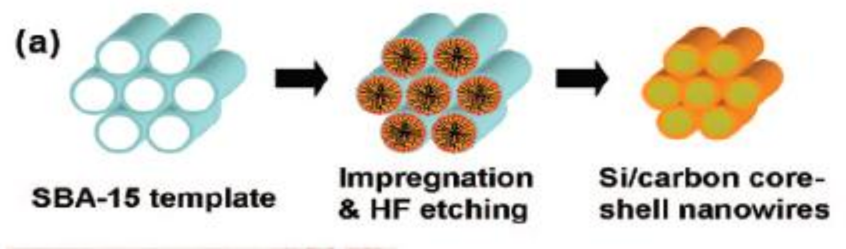
at electrode-electrolyte ***interface***

Electrode materials approaches

Carbon electrodes replaced by silicon nanowires

Future Nanostructure Silicon Anodes

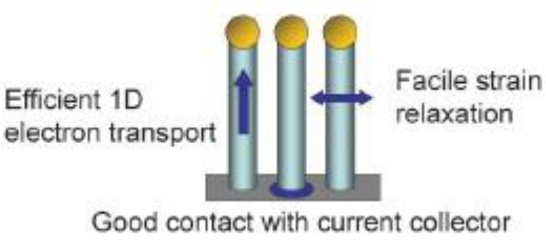
Silicon @ carbon core-shell anode



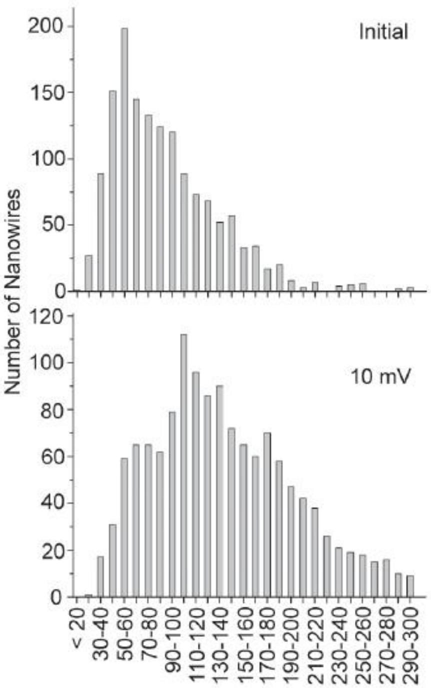
Charge capacity: 3163 mAh/g, retention @ 80 cycles: 87%

Kim and Cho, Nano Lett.,8, 11 (2008)

Silicon nanowire anode



Charge capacity
x 10 times,
Diameter changes
150%



Cui, Nature Nanotechnology, 3, 31 (2008)

Battery Anode Materials

Carbon anodes

$C_6 \longleftrightarrow LiC_6$

Theoretical capacity: 372 mAh/g

Silicon anodes

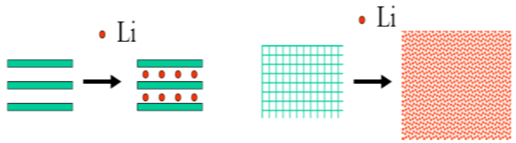
$Si_6 \longleftrightarrow Li_{4.4}Si$

Theoretical capacity: 4200 mAh/g

400% volume expansions

Chan, et al., Nano lett. 7, 490 (2007)

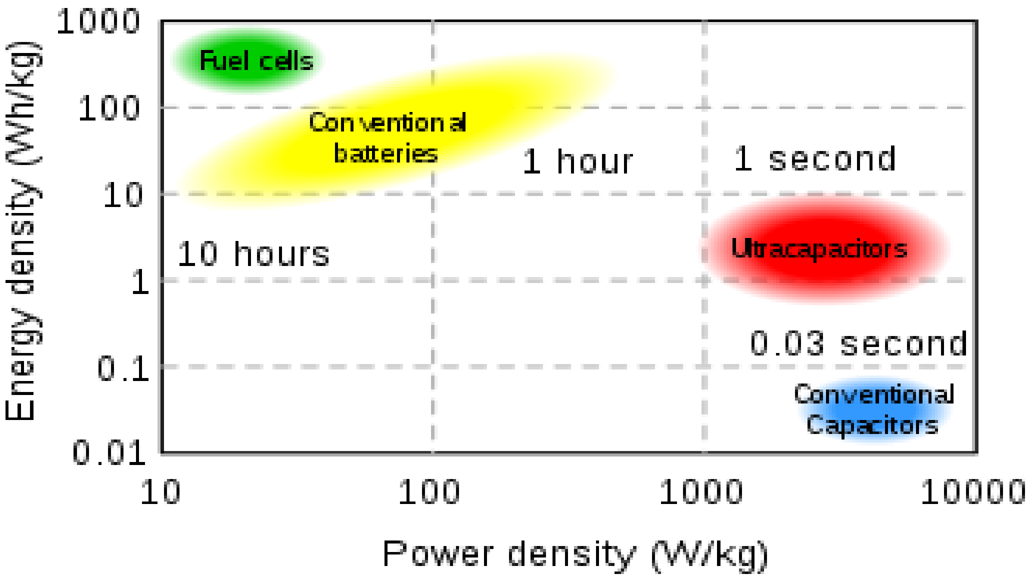
Future battery anodes



	Existing Tech.	Future Tech. New Materials
Mechanism	Intercalation	Displacement/alloy
Volume change	Small	Large
Li diffusion rate	Fast	Slow
Specific capacity	Low	High

Shorter cycling time, longer life time

Electrical Power Density – Energy Density Comparison

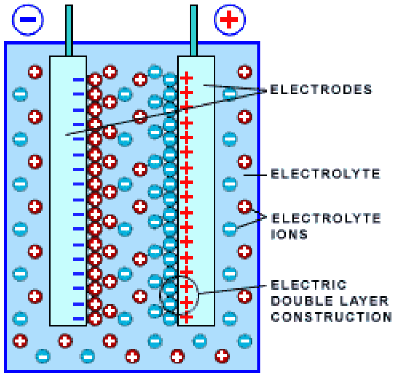


Ragone chart: EES device energy density vs. power density

Electrochemical Capacitors: Physical Charge Storage

Physical storage for electrical energy with charges on opposite insulator

High charge/discharge rates,
Low specific energy
unlimited cycle life



High ***surface area*** of electrode materials

Energy density

$1/C_t = (1/C_+ + 1/C_-)$

Dielectric polymer electrolyte

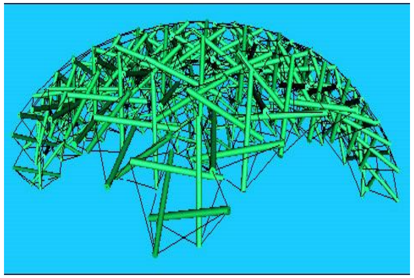
High cell voltage output limited by breakdown potential (1-3 V/cell)

Chu et al, science, 313, 334(2006)

Capacitor materials

Mixed metal oxides (RuO_2 and IrO_2, MnO_2 and $Li_4Ti_2O_{12}$) for symmetric capacitors
Polymers (PET, PPy and PANi) for symmetric/asymmetric capacitors

Wind and Kinetic Energy Conversions



Wind energy conversion from large balloon or deployable tensegrity polymer structures in folded small towed volumes



Applications of piezoelectric materials in other multifunctional structures

Objectives:

Demonstrate prototype multifunctional, lightweight devices and deployable structures, which convert mechanical motion and wind energy to electric power for scientific instruments and personal devices.

•Flexible and multiple degrees of freedom wind and other form of kinetic energy conversions.

•Piezoelectric device constructed with high strain polymers and compliant electrodes, capable of "stretching" in parallel with the target motion.

•Enhancement to emerging high altitude wind energy harvesting devices

Piezoelectric Polymers for Energy Harvesting

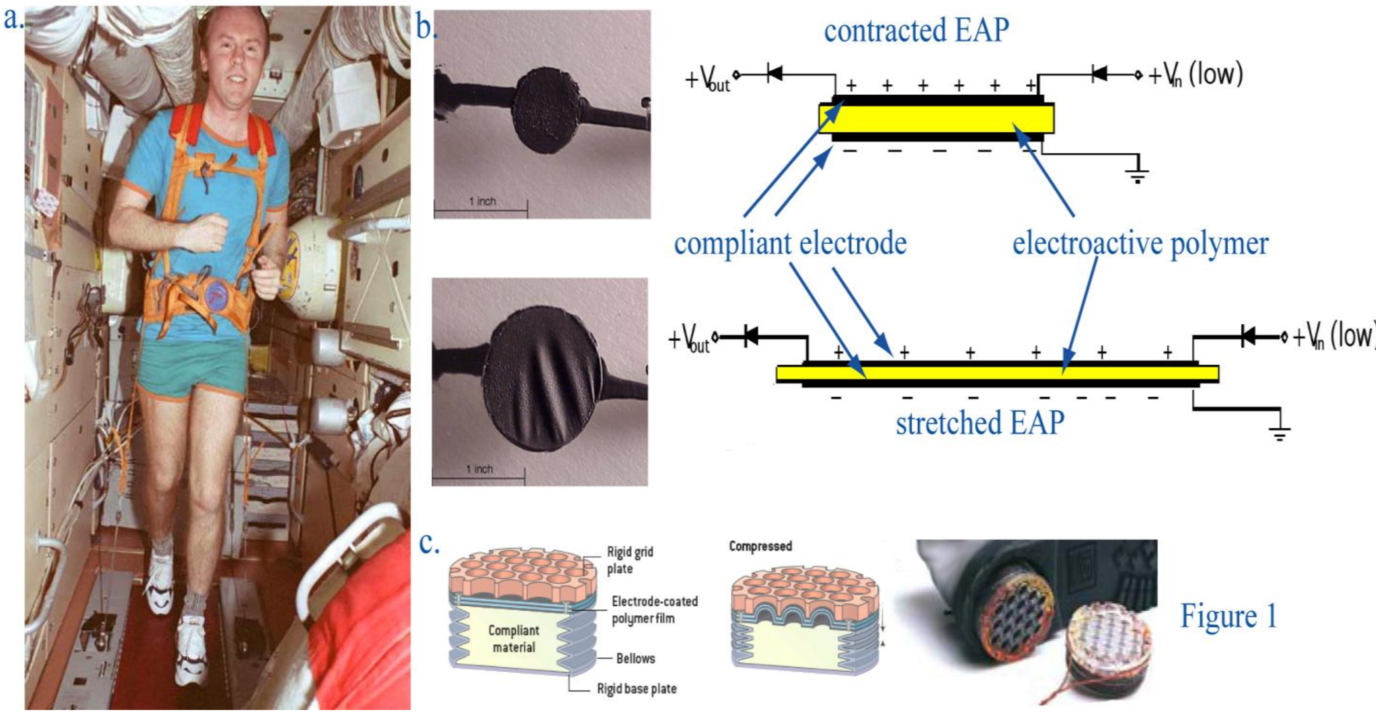


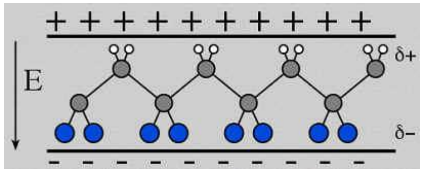
Figure 1

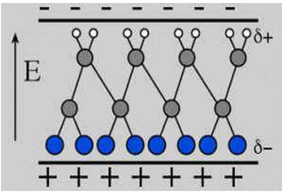
Collage showing (a) an astronaut engaged in typical countermeasure activity, (b) laboratory demonstration of contracted and stretched EAP film with accompanying schematics of operation mechanism of an EAP generator, and (c) a prototype shoe-strike power generator. The similar power generation can be achieved by chest pull exercise equipment.

* S. Ashley, “Artificial Muscles”, Scientific American, October 2003

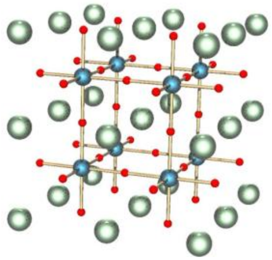
Piezoelectric Polymer Materials

Poly(vinylidene fluoride) (PVDF) Piezoelectric structures





Pervoskite ceramic structure
(PZT -- $^{XII}A^{2+VII}B^{4+}X^{2-}_{3}$)



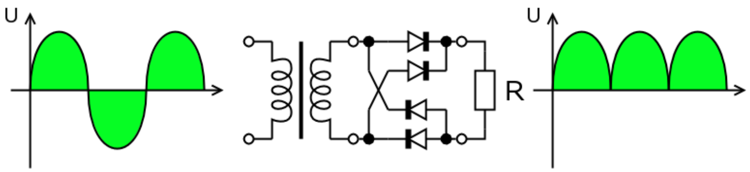
PVDF has direct piezoelectric and reverse piezoelectric effects

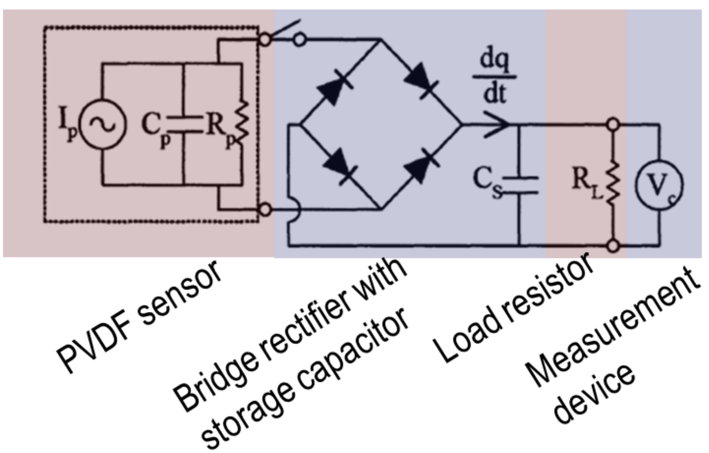
Piezoelectric effect: $\{D\}=[\alpha^{S}]\{E\} + [e]^{T}\{S\}$
Reverse piezoelectric effect: $\{T\}=[c^{E}]\{S\} - [e]\{$

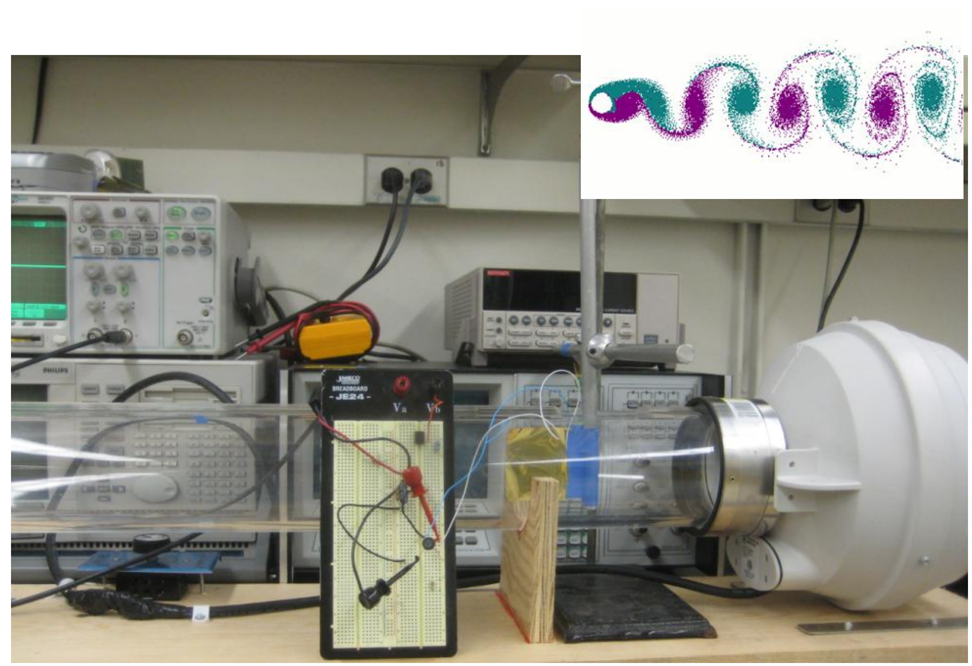
{D}: electric displacement vector
{T}: stress vector
[*e*]: dielectric permittivity matrix
[c^E]: matrix of elastic coefficients at constant electric field strength
{*S*}: strain vector
[α^S]: dielectric matrix at constant mechanical strain
{*E*}: electric field vector

Piezoelectric polymers expand or contract in an electrical field or generate an electrical charge when wind pressure is applied from tunnel

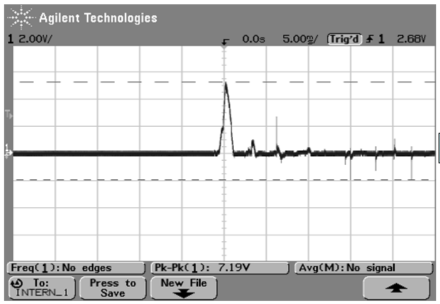
Experimental Set Up for Wind Energy Generation and Storage



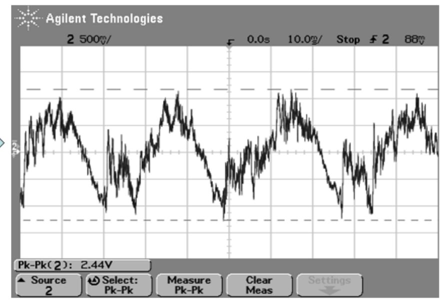




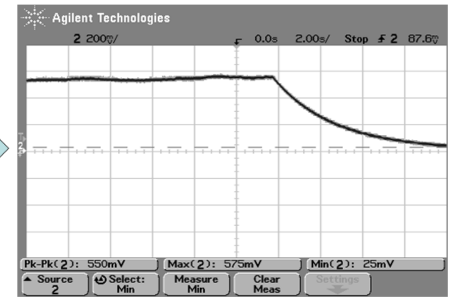
Experimental Results of Wind Energy Generation Output



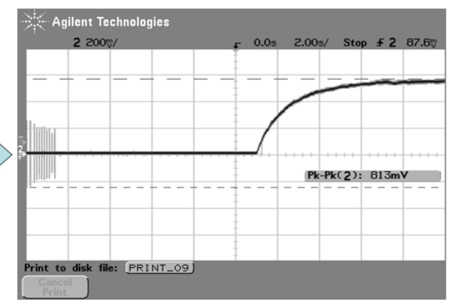
Tapping of PVDF will generate a voltage spike. Peak value depends on the force applied, the sample thickness, and even the boundary conditions of the sample.



Periodic signal is generated due to Karman Vortex Street. Storage capacitor is dismounted; Load resistor equals to 800K ohms.



Storage capacitor is 4.7μF; Power is dropping down due to sudden stop of wind flow.



Storage capacitor is 4.7μF; Power is ramping up due to wind flow.

Precision I-V measurements

Materials Optimizations

Thickness

110 µm

too stiff; barely move under 15 mph wind without tail attached.

With tail attached, Au-coated sample provides 400 mV

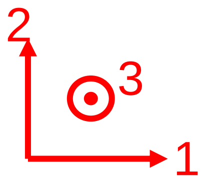
28 µm

flexible; easily vibrate; less number of molecular chains causes less charge

Au-coated sample provides 120~150 mV

52 µm

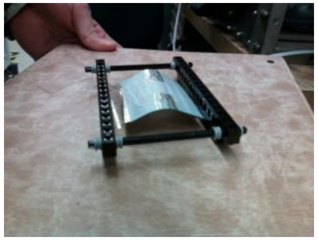
Voltage can go up to almost 700 mV

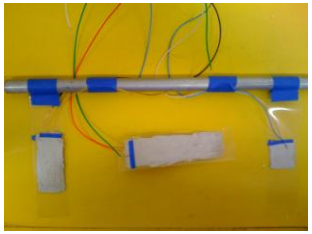


Orientation

Polarization makes difference between pre-stretched direction 1 and direction 2

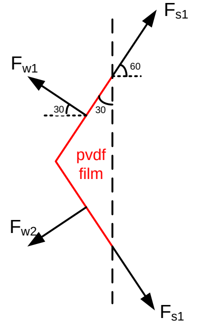
d_{31}, d_{32}

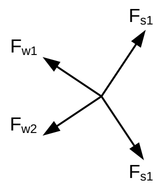




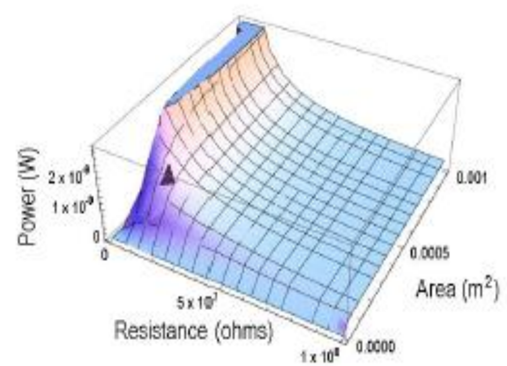
Mathematical Analysis of Power Generation and Optimizations

$$P_{peak} = V^2/R = (e_{31}AS_1\omega)^2R/(1 + (\omega CR)^2)$$

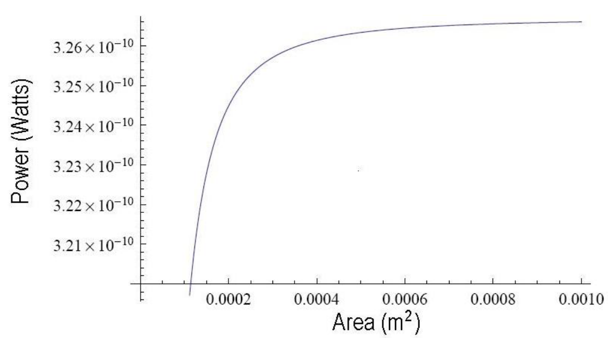


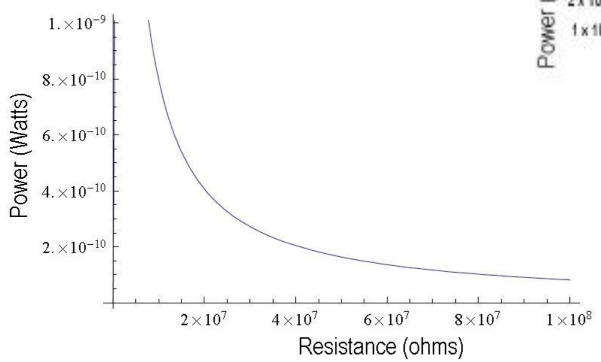


- e_{31}: piezoelectric coefficient constant of direction 3 respect to direction 1
- A: sample area
- S_1: sample strain
- R_L: load resistance
- C: sample parasitic capacitor



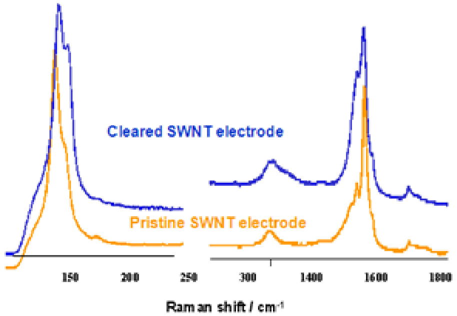
Optimization of piezoelectric active areas and load resistances



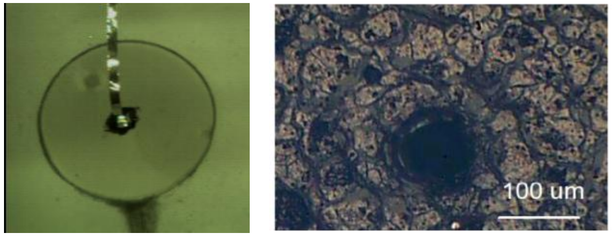


Nanostructure Electrode Materials for Piezoelectric Conversion

Self clearing electrode

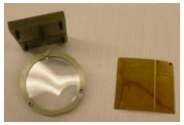


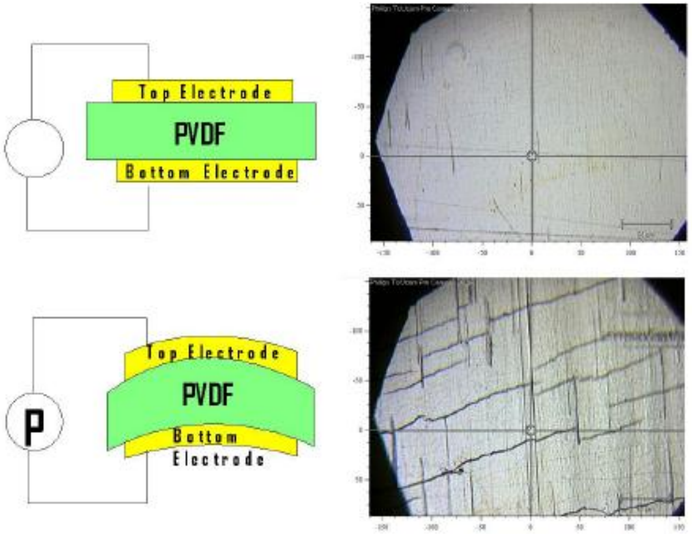
Raman analysis of the structure changes of carbon nanotube electrode in the cleared area, which prevent premature failures of film during actuation



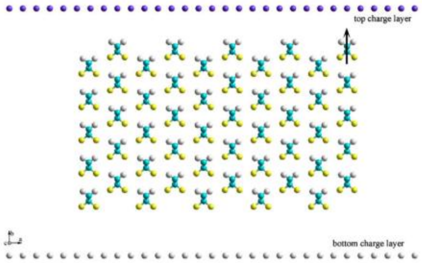
The clearing events prevent premature failures of film during actuation with increasing voltage.

Fatigue metal electrode

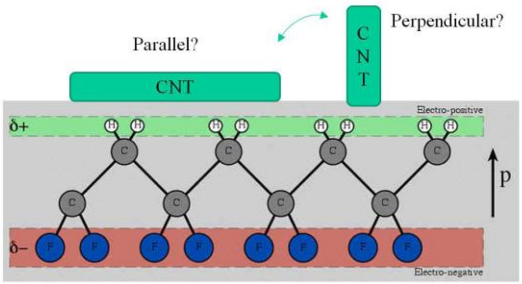




Yuan et al, Advanced Materials, 3, **621-625,** (2008)
Yu et al, App. Phys. Lett., **95**, 192904 (2009).



Novel electrodes for improved device performance and efficiency



Conclusions

A prototype of an energy harvestor for wind energy using piezoelectric materials is proposed and demonstrated.

In 20 MPH wind condition, the harvestor, which has area of 4 $inch^2$, is able to collect ~1μW electrical power.

Optimized thickness and active areas and resistance load are obtained under typical variable wind speed

Other Future Plan

Electrodes

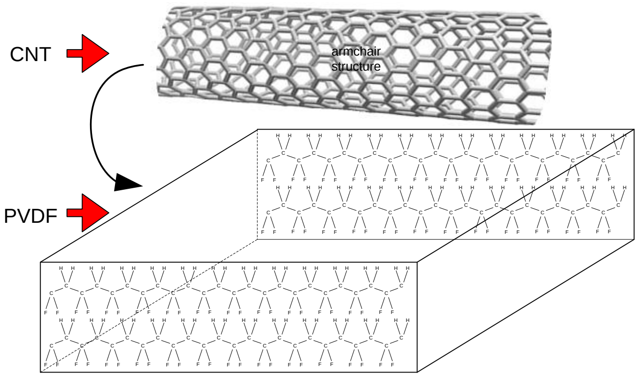
- Carbon Nanotube and other alternatives

Fluid dynamics calculation

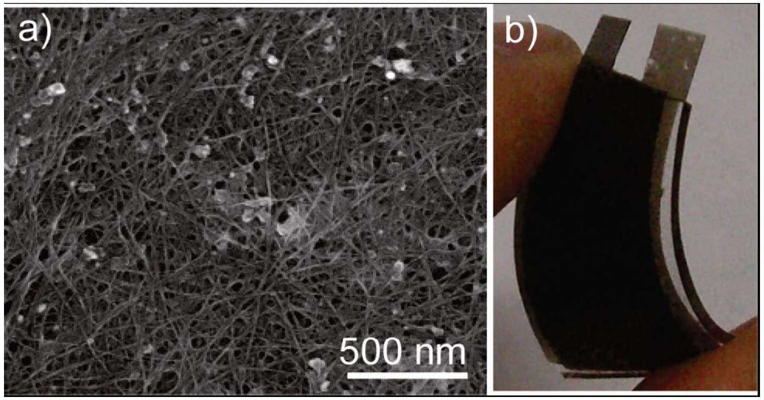
- Pressure difference in Vortex Street
- Coupled simulation of fluid and solid

Circuit improve, measurement

- Impedance matching calculation
- Ultra low current measurement

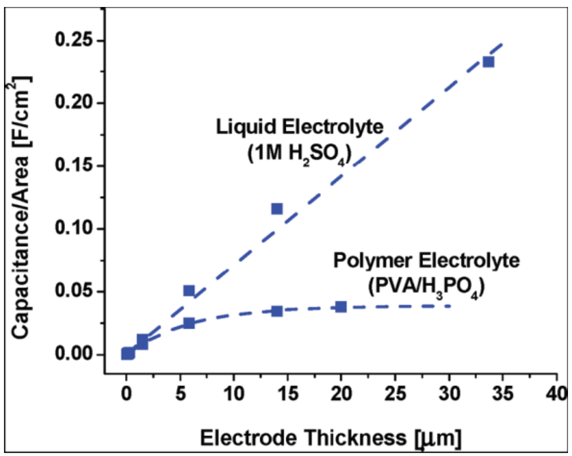


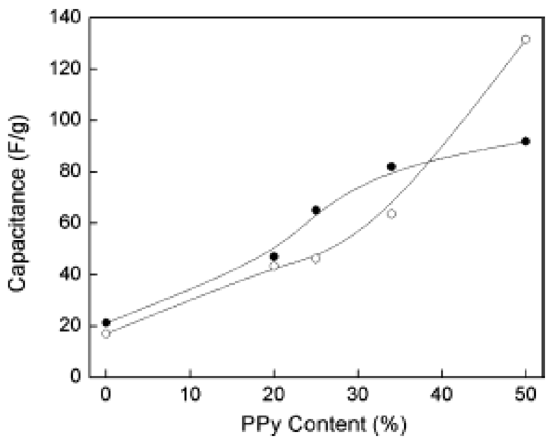
Carbon Nanotube Electrodes: Printable Film Capacitors



(a) Scanning electron microscopy image of as-deposited SWCNT networks. (b) Thin film supercapacitor using sprayed SWCNT films on PET as electrodes and a PVA/H3PO4 based polymer electrolyte as both electrolyte and separator.

Kaempgen, et al, 8, 1872 (2009)

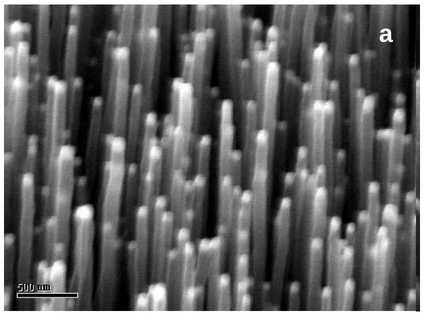


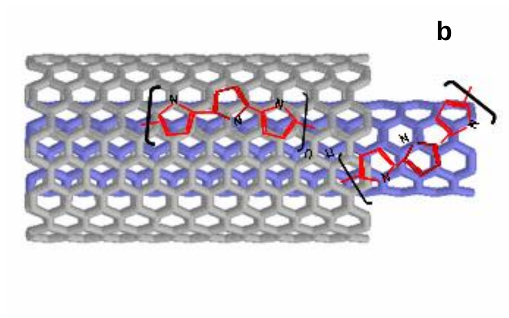


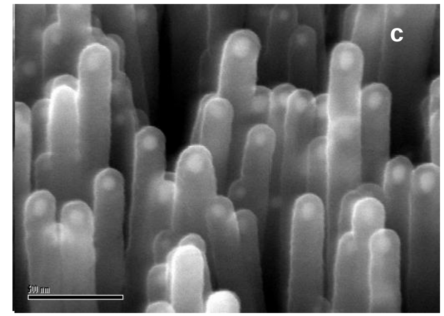
Oh et al, Synt. Met., 158,638(2008)

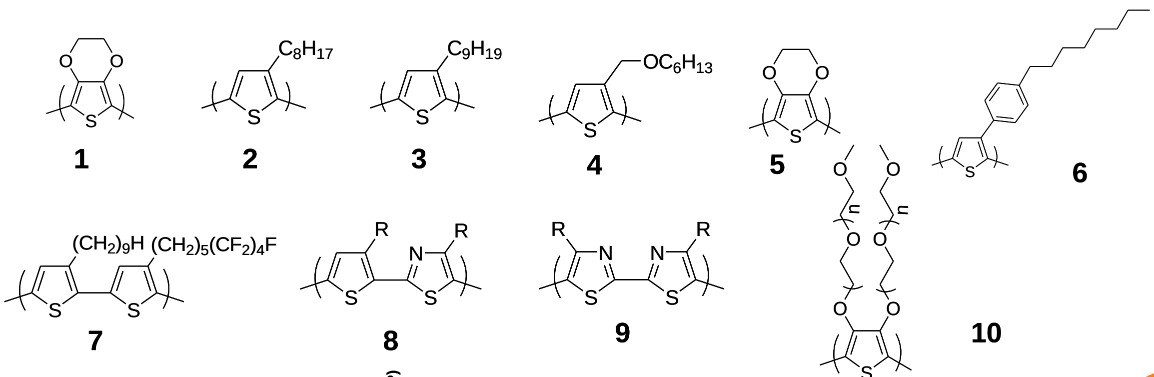
Left: Thickness dependence of the capacitance per area for CNT films comparing a liquid (1 M H_2SO_4) and a gel electrolyte (PVA/H_3PO_4), *Right:* Dependence of specific capacitance on wt. % of PPy in SWNT-Ppy nanocomposites determined by cyclic voltammetry (open circles) and galvanostatic charge-discharge measurements (closed circles).

Conducting Polymer Composites: Modified Surface States

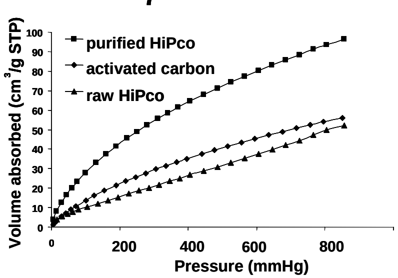


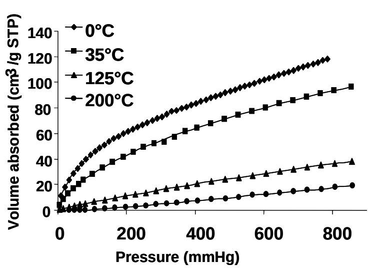


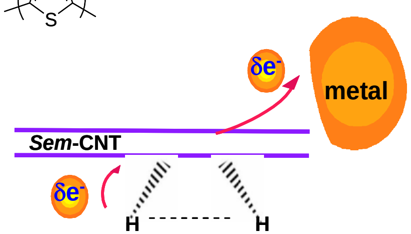


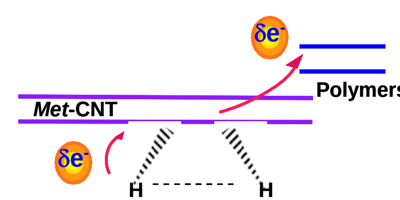


- Electron-rich vs electron-deficient
- Water solubility
- Regioregular vs. regiorandom
- Side-chains

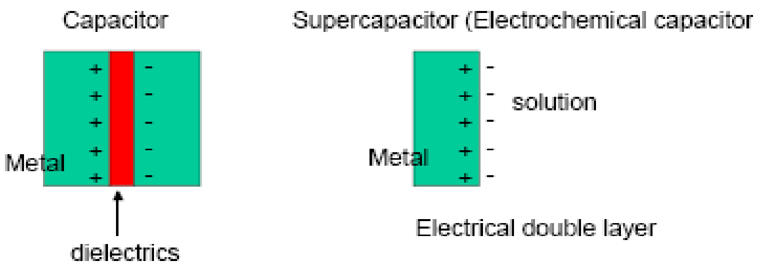




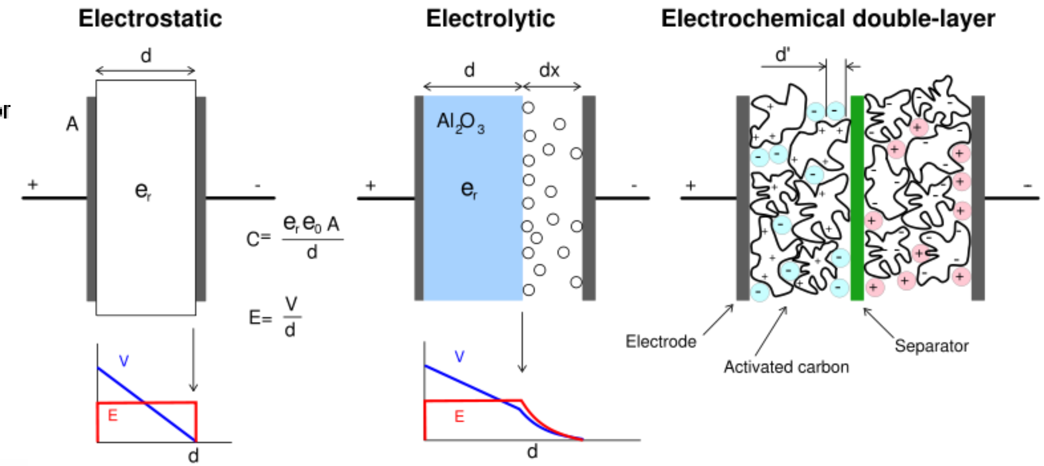


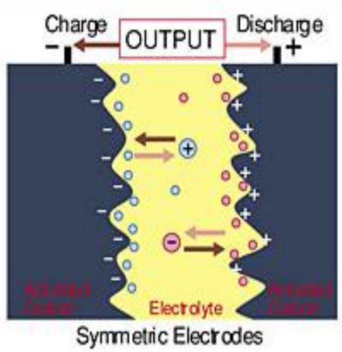


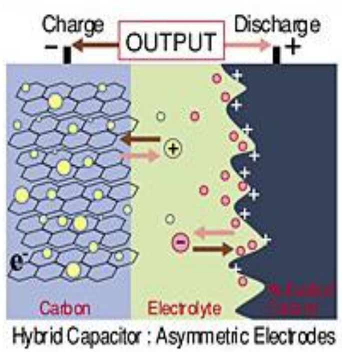
Capacitors and Hybrid Capacitors

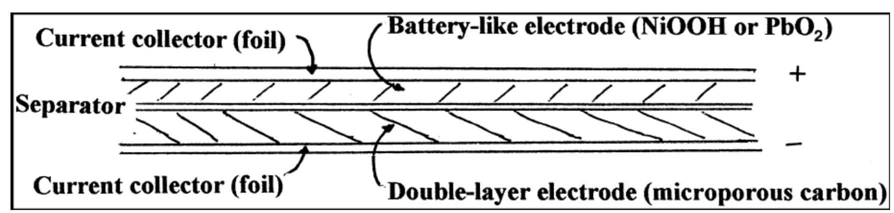


$$E = \frac{1}{2} C V^2$$





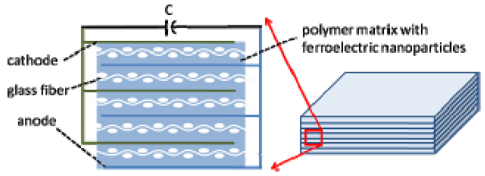




Electrochemical difference between EDLC and Lithium Ion Capacitors

$1/C_{EC} = (1/C_1 + 1/C_2)$ $1/C_{EC} = (1/C_1 + 1/C_2)$, $C_{EC} \sim C_1$ ($C_1 << C_2$)

Multifunctional Materials for Capacitive Energy Storage



$$C = \varepsilon \frac{A(1 - 2\nu x)}{h(1 + x)}$$

ε is the effective dielectric permittivity of the composite, A is the electrode area, and ν is the Poisson's ratio of the composite

Matrices

- PMMA (only one discussed in this talk)
- BECy
- PolyDCPD
- PMMA- Poly (methyl methacrylate)

Fillers

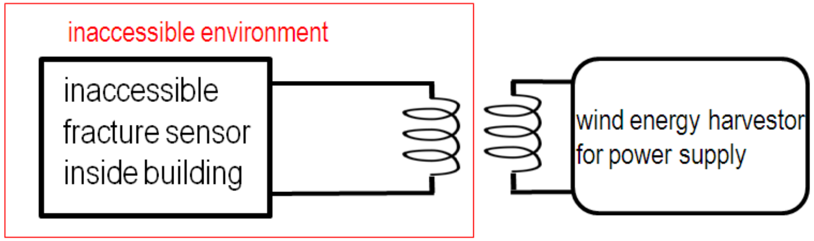
- Insulating ceramics ($BaTiO_3$, $CaCu_3Ti_4O_{12}$ (CCTO), ZrW_2O_8)
- MWCNT, Al, PANI, Clay, Montmorillonite (MMT)

System	Permittivity	tanδ
40% as-received $BaTiO_3$	4.4-4.5	0.003-0.05
Functionalized CNT-COOH	0-93.3	>7.92
CNT-COOH added to $BaTiO_3$ composite	8.9-52.8	0.159-265
Composite with GPS-funcionalized $BaTiO_3$	11.2-80.8	0.164-26.8
Nanoclay, CNT-COOH, and $BaTiO_3$ composite	9.2-9.6	0.004-0.007
Quaternay composite sputter coated with silver	17.0-18.3	0.007-0.10

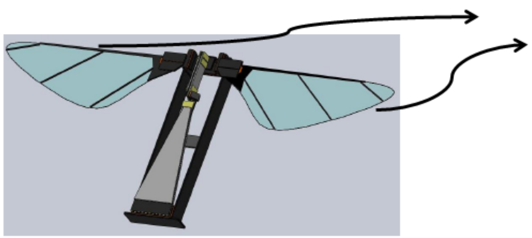
Energy Storage and Power Transmission

- Power supply for low power consumption device, such as wireless sensors and portable devices

- Wireless power transmission for inaccessible devices



- Power Storage for Miniature Robotic Devices



Wings could be made by PVDF to provide power and reduce the size of the batteries

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