AFOSR-MURI on Energy Harvesting and Storage Systems (EHSS)

Period: May/2006-May/2011
Funding: $6M
Dr. B. "Les" Lee *(Air Force Office of Scientific Research)*, ***PM***
Dr. Joan Fuller *(Air Force Office of Scientific Research)*, ***Co-PM***
Dr. Victor Giurgiutiu *(Air Force Office of Scientific Research)*, ***Co-PM***

Researchers:
Minoru Taya, PI , UW

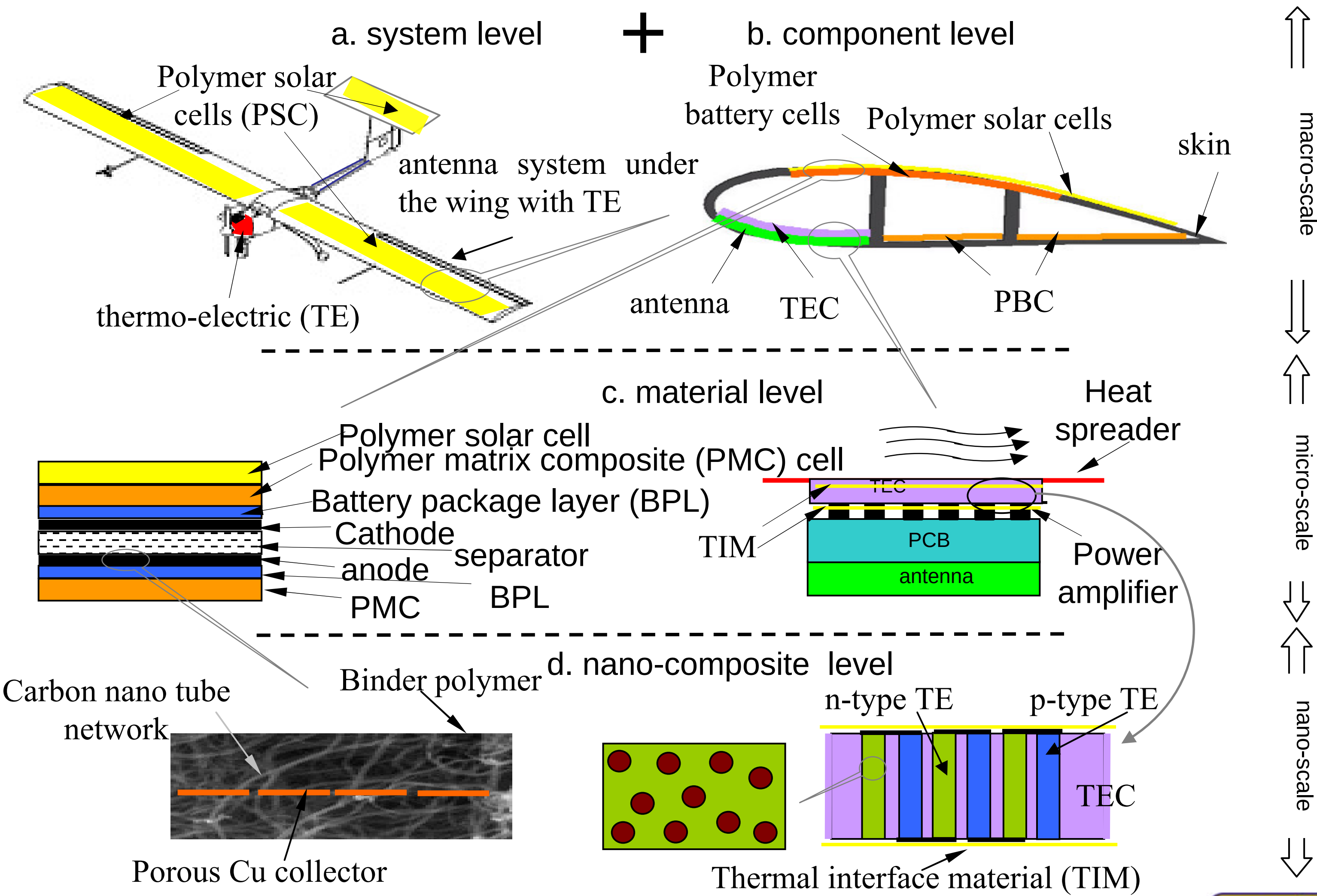
UW: Chunye Xu (ME), G. Cao(MSE),
S. Jenekhe(ChemE), Y. Kuga(EE)
CU: M. Dunn, K. Maute, R. Yang
UCLA : T. Hahn, S Ju
VPI : D. Inman

Collaborating Industry, Boeing, etc.

Goal : To develop a set of energy harvesting materials and systems for future AF vehicles

Aug 25,2006

Multi-scale approach to design of energy harvesting aircraft systems



MURI - EHSS Tasks

A. Design Tools for Multifunctional Materials and Structures (Dunn, Maute and Taya)

B. Energy Harvesters based on thermoelectrics (Yang and Taya)

C. Energy harvester based on polymer solar cells (Jenekhe ,Xu, Nango)

D. Manufacturing and durability of energy harvesting structures (Ju and Hahn)

E. Design of Energy Storage System (Xu, Cao, Kuga)

F. Electric System Design (Kuga)

G. Multimode Energy Harvesting for ISR/MAV Missions (Inman)

H. Educational Programs (Taya and Dunn)

I. Validation of the Proposed EHSS (all)

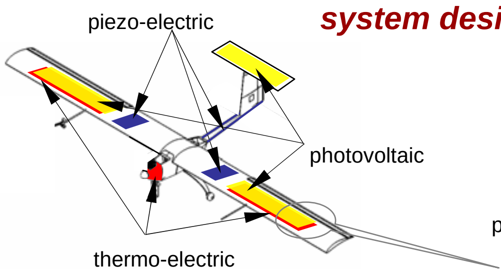
Tasks and Milestones

Milestones and Deliverables	The first 3 years			The last 2 years	
	1^{st} year	2^{nd} year	3^{rd} year	4^{th} year	5^{th}year
A Design Tool-component level					
A1 Electrochemo-mechanical coupling Model		▼			
A2 Multi-scale, multi-physics constitutive Model			▼		
A3 Design optimization model					▼
B TE energy harvester					
B1 Optimized TE materials	▼				
B2 Processing of TE materials		▼			
B3 Process TE unit			▼		
B4 Process of TE models				▼	
B5 Integration and testing with heat sources					▼
C Polymer solar cell harvester					
C1 Optimization of donor-acceptor copolymers by DFT		▼			
C2 Process and characterization of molecular hetero junction PSC			▼		
C3 Demo of PSC sheet with goal of 10% Efficiency				▼	
C4 Process and demo of layer PSC About with 20% or more efficiency					▼
D Manufacturing and durability					
D1 Multifunctional manufacturing and integration schemes		▼			
D2-1 Multifunctional characterization capability	▼				
D2-2 Existing state-of-the art materials and material forms			▼		
D2-3 1^{st} generations of new materials				▼	
D2-4 2^{nd} generations of optimized new materials					▼
E Energy storage system					
E1 Cathode material system	▼				
E2 Anodic material system		▼			
E3 Environmentally storage electrolyte system			▼		
E4 Demo of PBC			▼		
E5 Demo of super capacity				▼	
E6 Integration of PBC and PSC					▼
F Electrical system design					
F1 Power conditioner	▼				
F2 Hybrid power unit		▼			
F3 Wireless system			▼		
F4 Overall electrical system design					▼
G Multimode Energy Harvesting					
G1 System analysis of UAV		▼			
G2 Design rules					▼
H Education Programs					▼
I Validations					
I1 components				▼	
I2 UAV demonstrator					▼

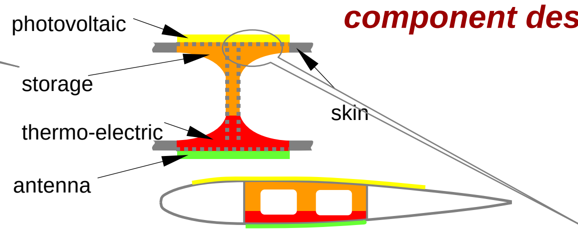
Computational Design Tool Development

CU – Multi-Physics Optimization Toolbox

Problem	Multiphysics	Material	Optimizer	Sensitivity	Criteria
2-D	Thermo-mechanical	Gold	SQP	Direct	Mass
3-D	Electro-thermo-mechanical	Polysilicon	MMA	Adjoint	Displacement
Harmonic	Electro-chemical-mech.	Aluminum	SLP	FD ►	Stress
▼	▼	▼	▼		Temperature
					Current
					Power
					▼



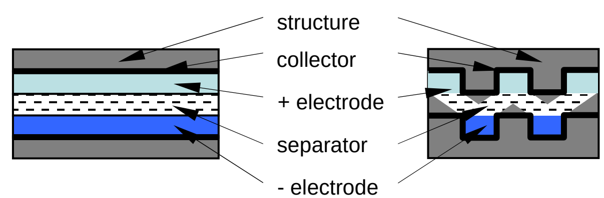
system design
- overall system design
- placement of EHS systems
- power storage management



component design
- mechanical design
- coupled analysis & design
- integration

material design

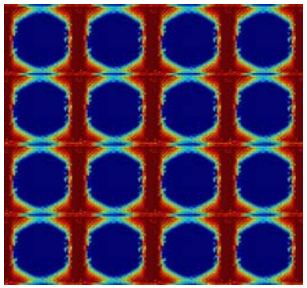
- structural battery design
- multi-physics analysis

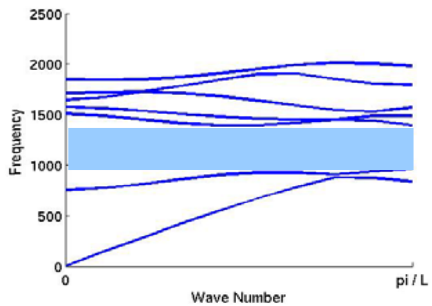


Multiphysics Material & Micro Device Design

Phononic Metamaterials Design

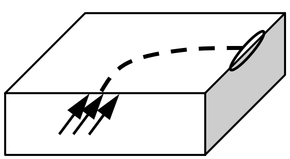
Bandgap Metamaterials

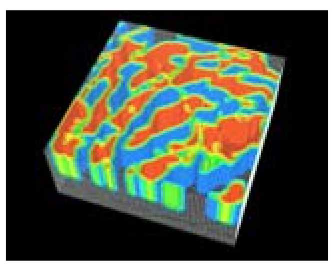




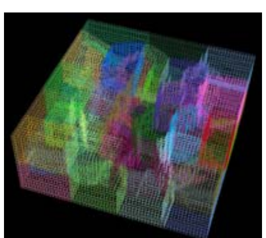
Application-Specific Metamaterials

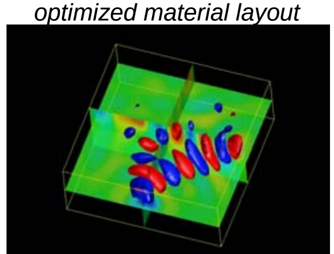
surface wave guide





optimized material layout

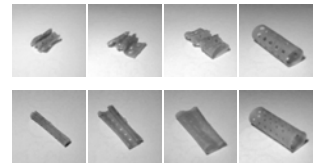




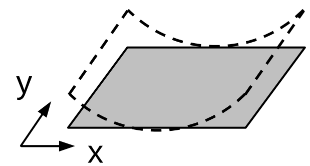
decomposed FE mesh

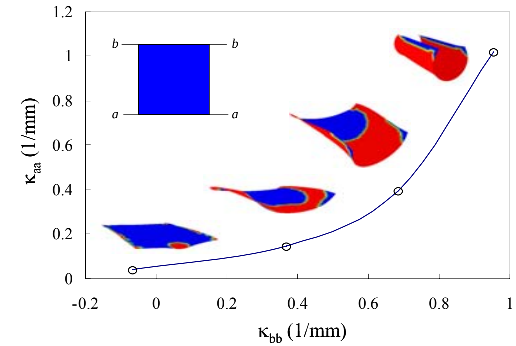
wavefield in a the optimized material

Photoelastic Metamaterials Design

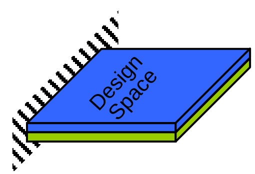


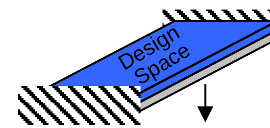
uniaxial bending

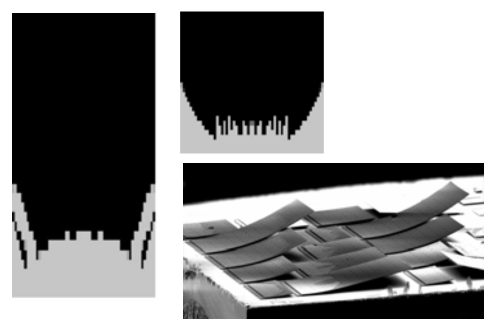


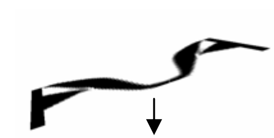


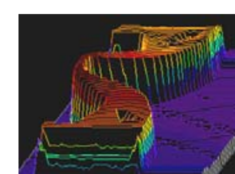
Electro-Mechanical Microsystem Design











optimized gold pattern

optimized actuator

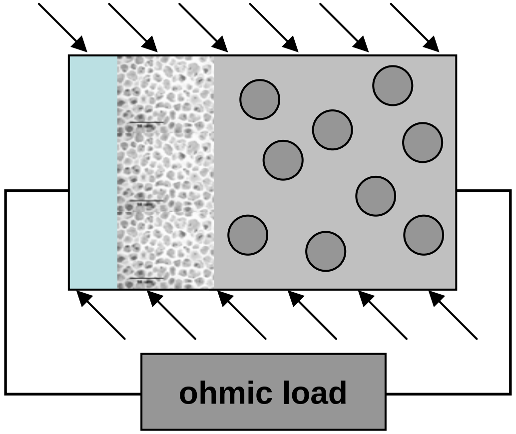
Design Tools for EH&S Composites

CU - Topology Optimization Toolbox

Problem	Multiphysics	Material	Optimizer	Sensitivity	Criteria
2-D	Thermo-mechanical	Gold	SQP	Direct	Mass
3-D	Electro-thermo-mechanical	Polysilicon	MMA	Adjoint	Displacement
Harmonic	Electro-chemo-mechanical	Aluminum	SLP	FD ▶	Stress
▼	▼	▼	▼		Temperature
					Current
					Power
					▼

Focus I: Design of Batteries with Load-Barring Capabilities

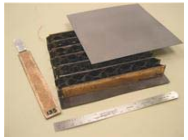
maximize energy storage & stiffness & strength



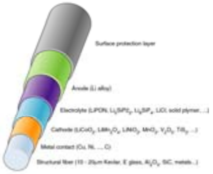
Collaboration with local companies & labs

Boundless Corporation

Innovative Energy Storage for High-P



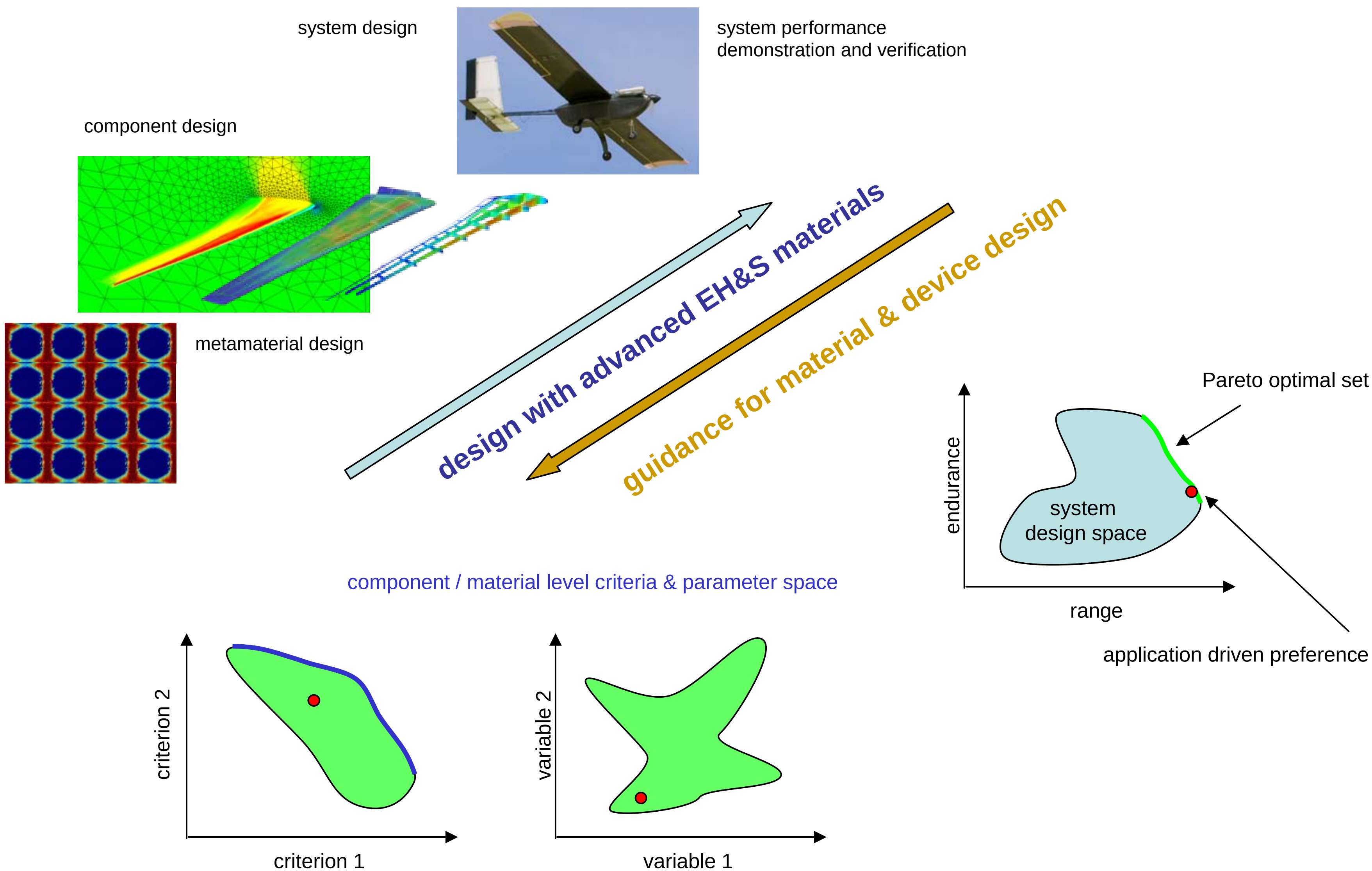
ITN ENERGY SYSTEMS INC.



NREL

Preliminary work: developed and implemented a micro-structural electrochemical-mechanical battery finite element model

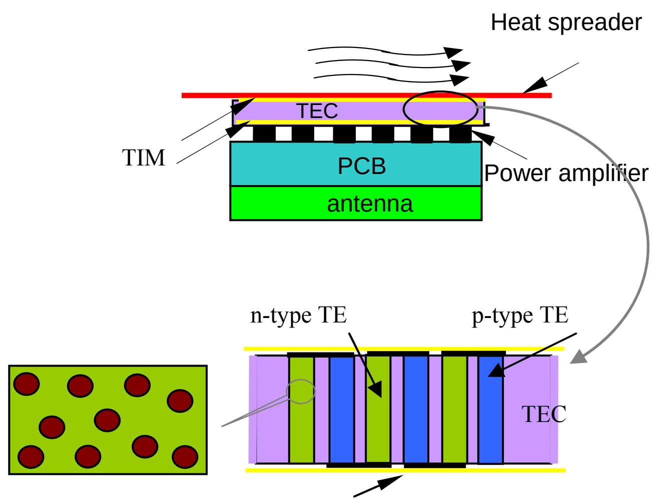
Design Tools for EH&S Enabled Vehicles

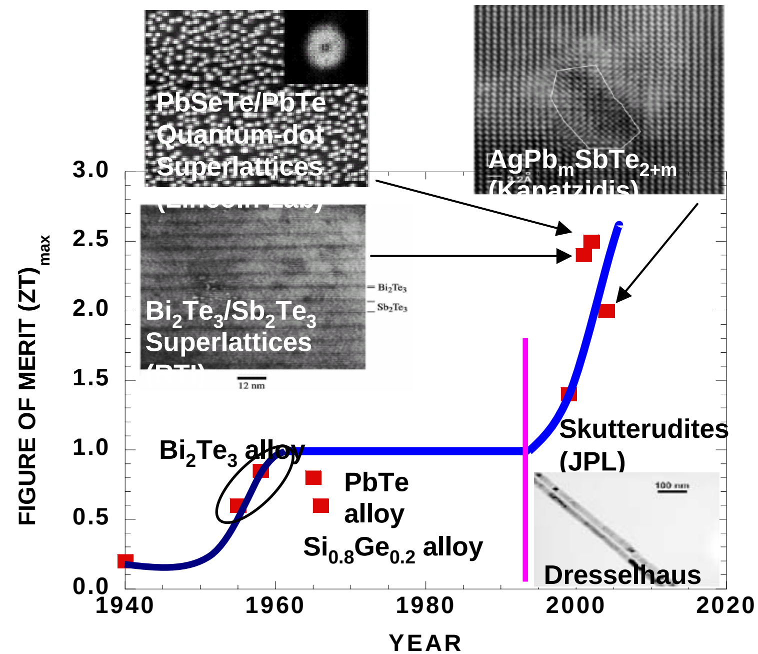


Nanocomposite Thermoelectric Materials and Energy Harvesting System

Statement of the Work (TE)

- Materials, Devices, & System





State-of-the-art Thermoelectrics

Nanocomposites - Bulk Thermoelectric Materials with Embedded Nanostructures

- Cost-Effective
- Mass Production
- A Paradigm Shift on TE Research

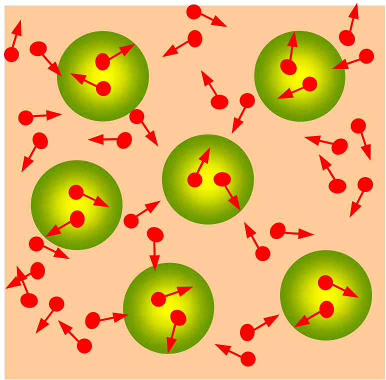
Expectations

- Reduced thermal conductivity.
- Electrical conductivity comparable to or better than bulk.
- Increased Seebeck Coefficient.
- Overall Enhanced ZT by a factor of 2-5.

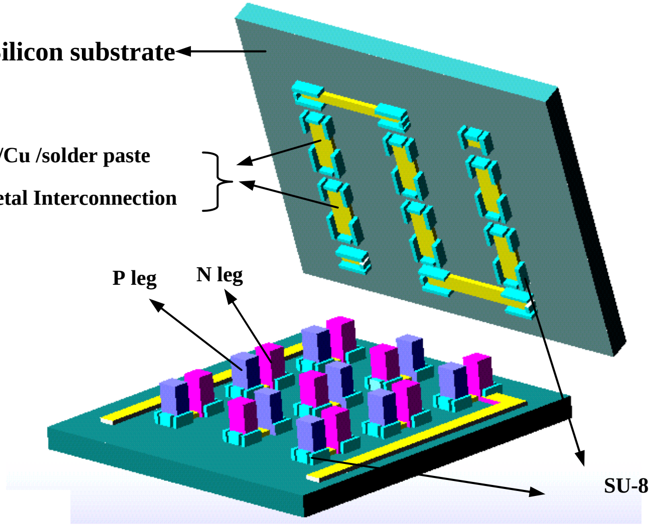
CU-Tasks on Thermoelectrics

- **Design and characterize thermoelectric nanocomposites**
- **Design of TE devices**
- **Testing TE devices and system integration**

1. Develop atomic simulation tools to study the thermal conductivity, Seebeck coefficient and electrical conductivity of nanocomposites and design nanocomposites with effective ZT = 1.5-4.

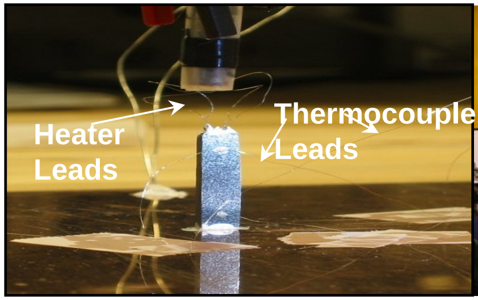


3. Develop tools to design thermoelectric devices and to predict the performance of TE-subsystem in AF environments
4. Assist UW to develop the fabrication process for nanocomposite TE devices and test TE devices.

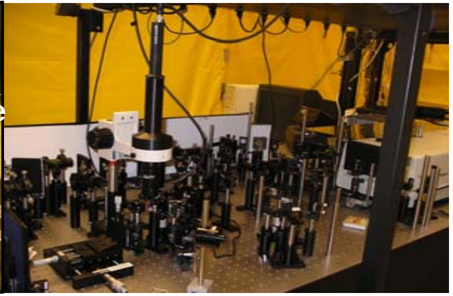


Schematic drawing of silicon-based TE device (Pick & Place process, TE legs are made of nanocomposites)

2. Develop tools to measure the thermoelectric properties of nanocomposite sample made in UW.



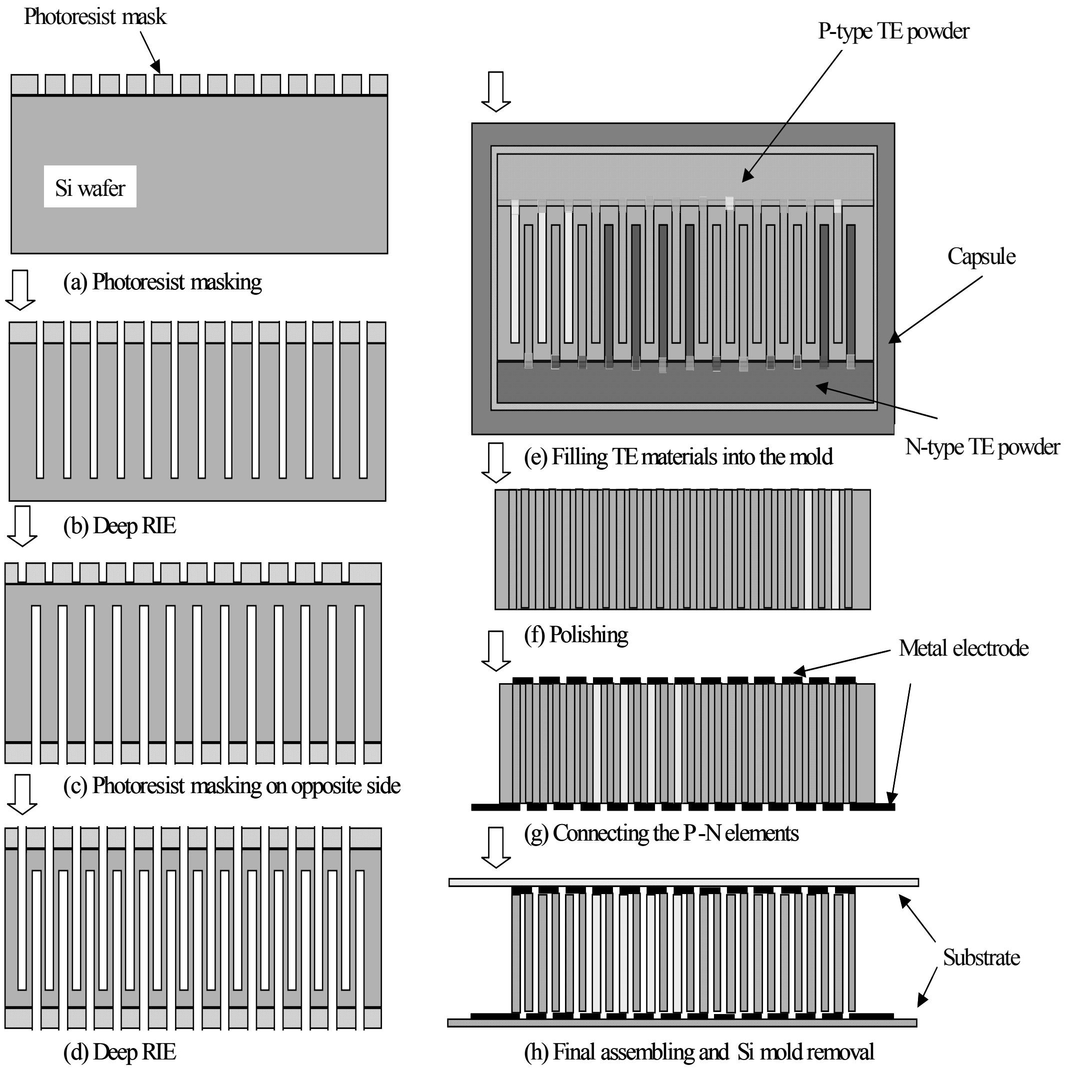
Conventional Four-Probe method



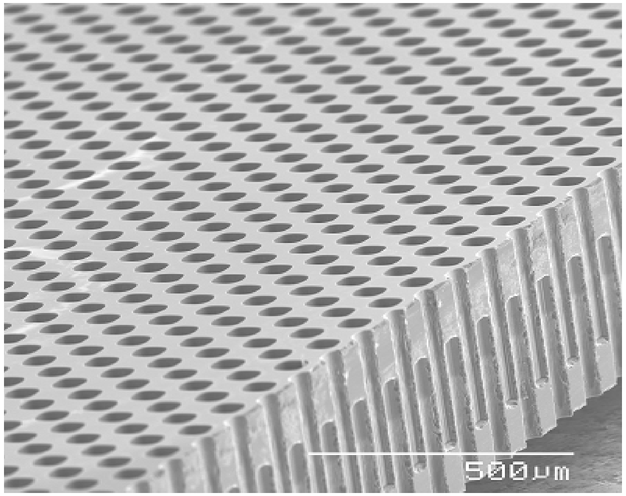
Sub-ps Pump-Probe method

UW tasks – Nanocomposite synthesis & Device Fabrication

Fabrication process for nanocomposite TE devices

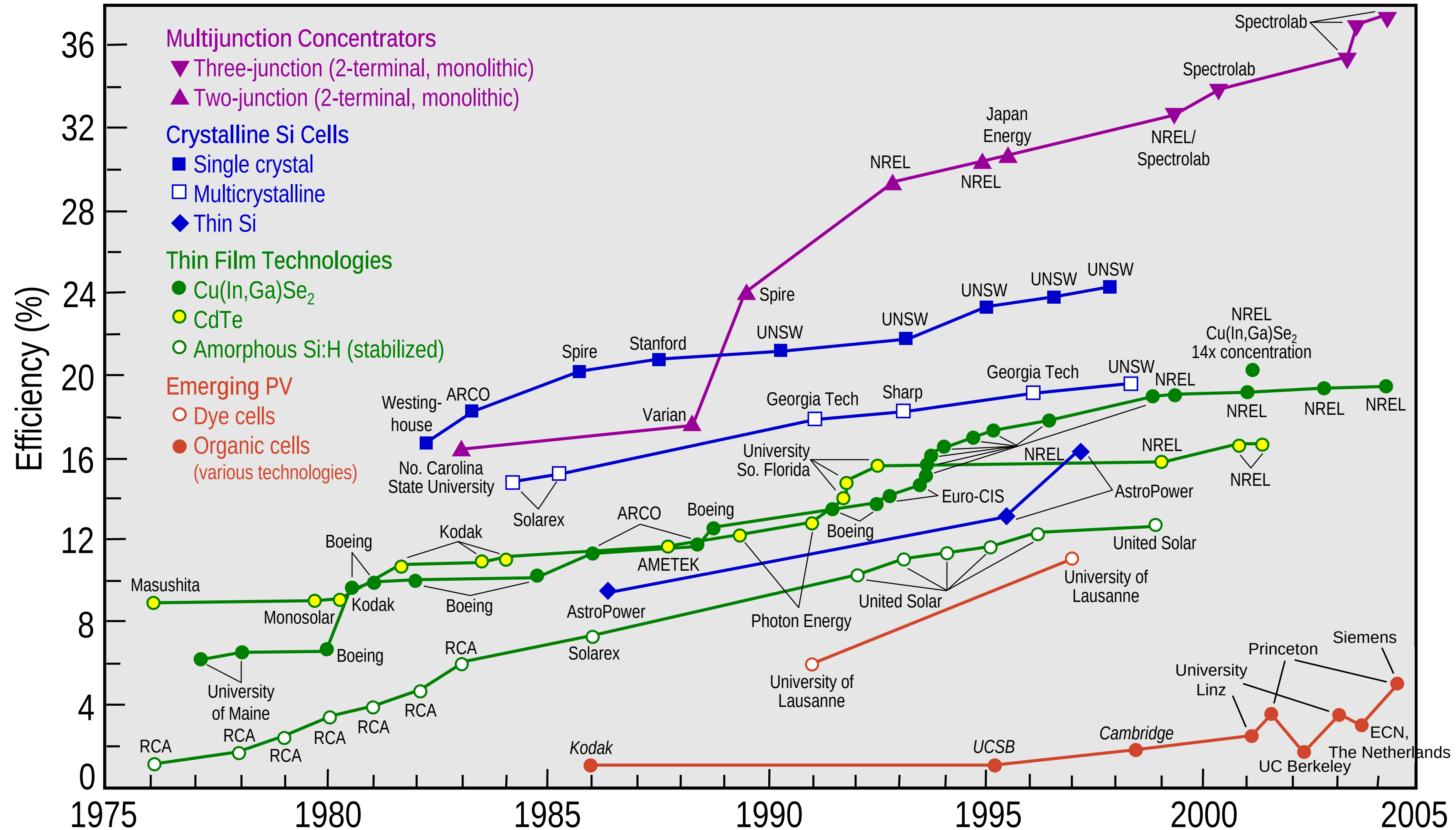


Microfabrication processes to make micro/mini TE devices with the use of mechanical alloyed nanocomposite powder



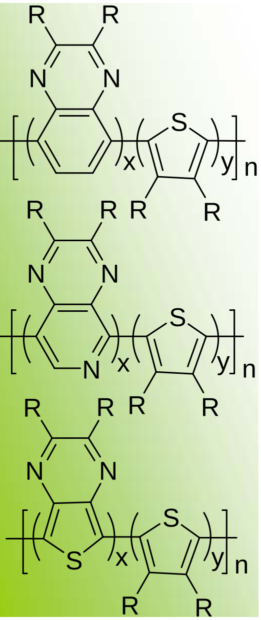
Ref. : J.F. Li et al.
Sensors and Actuators A **108** (2003) 97-102.

Best Research-Cell Efficiencies

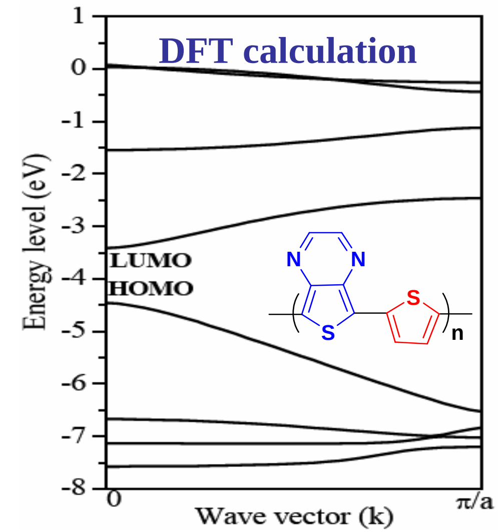


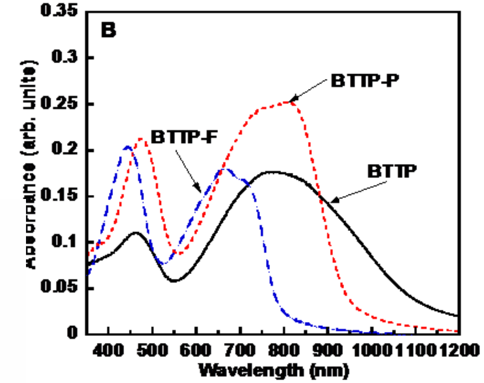
Taken from a presentation by Baldwin “Energy Efficiency and Renewable Energy; Energy: A 21st Century Perspective; National Academy of Engineering; June 2, 2005”

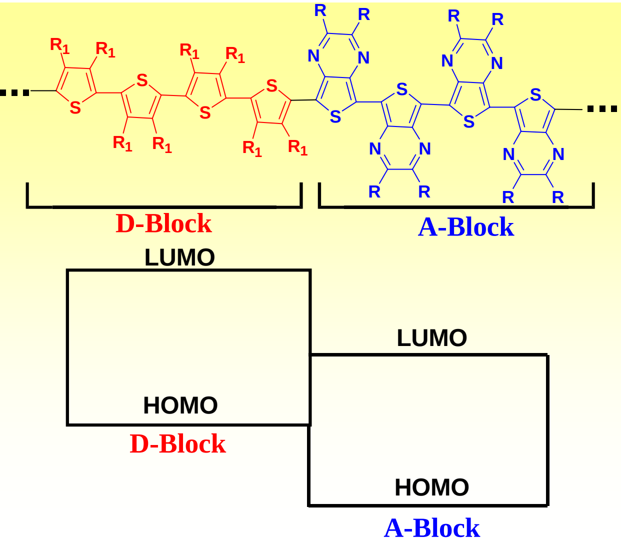
Task on Energy Harvesters Based on Polymer Solar Cells

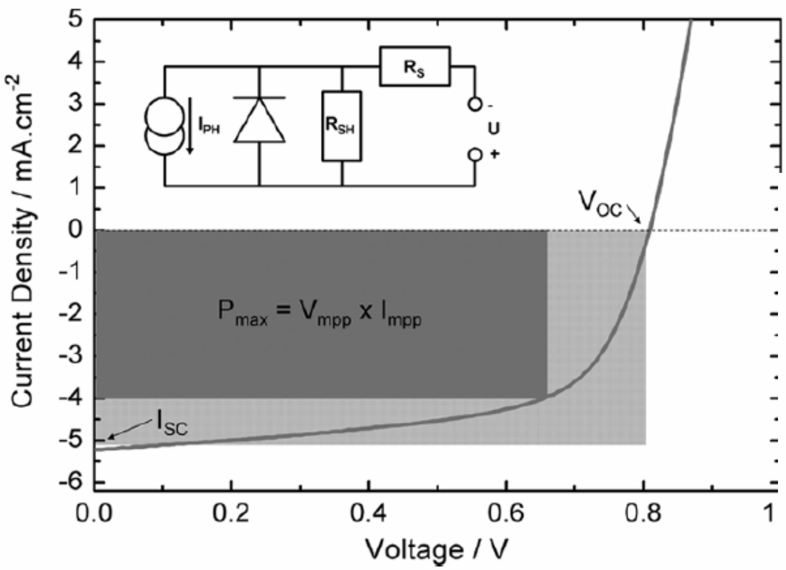


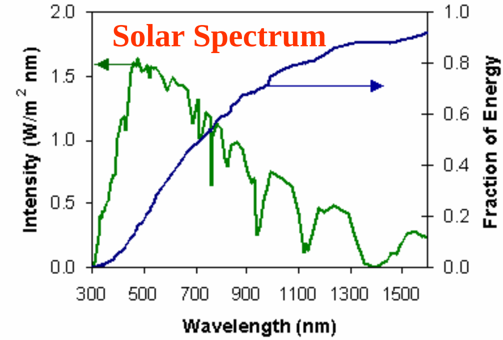
1. Design and Synthesis of D-A Copolymers
   - Band structure engineering by DFT
   - Visible-NIR absorption to match solar spectrum
   - High carrier mobilities
2. Fabrication and Evaluation of Solar Cells
   - Layered Heterojuction (LH)
   - Bulk Heterojuction (BH)
3. Synthesis and Evaluation of Molecular Heterojuction (MH) Cells
4. Fabrication and Evaluation of Hybrid Organic / Inorganic Solar Cells
5. Integration of Polymer Solar Cells with Other EHSS Components





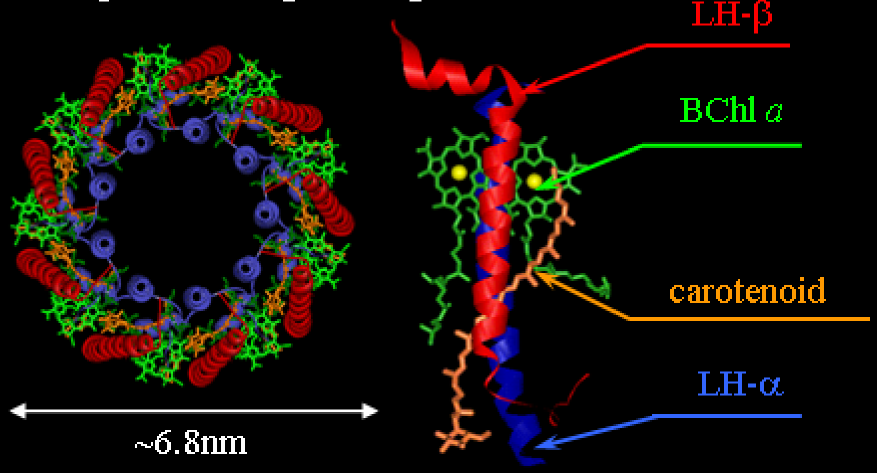






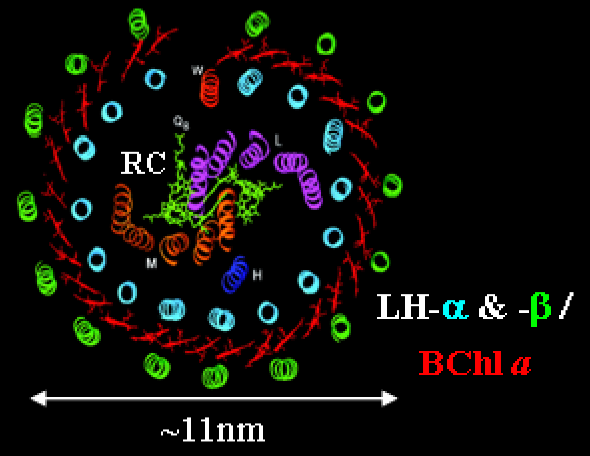
Nature: Purple Photosynthetic Bacteria

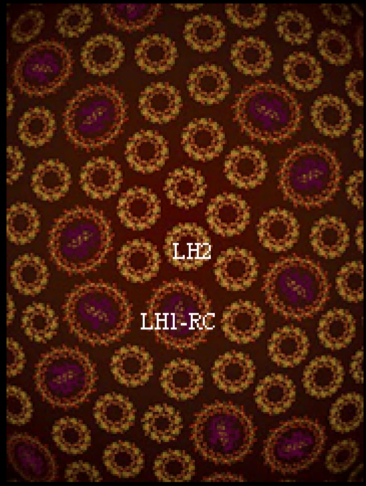
LH2 complex from *Rps.acidophila* 10050



R.J. Cogdell, *et. al*, *Nature*, **374**, 517, (**1995**)

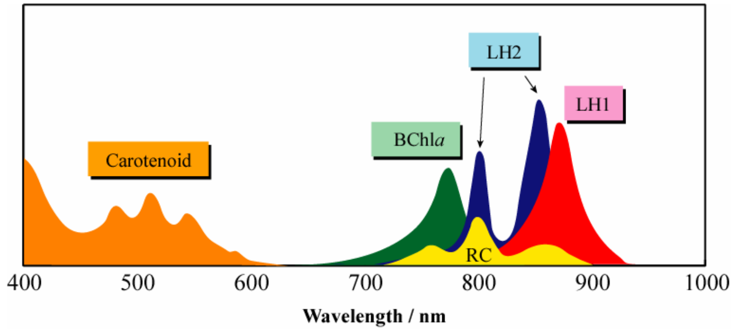
LH1-RC core complex from *Rps.palustris*



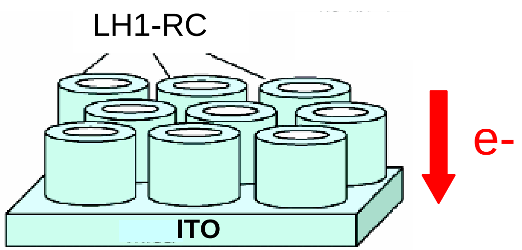


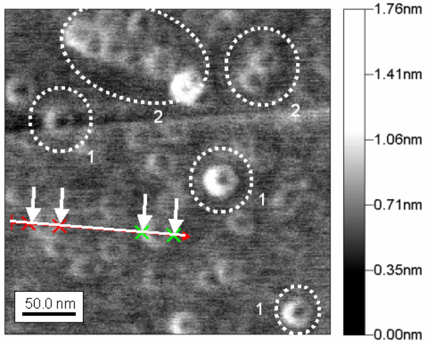
R.J. Cogdell, *et al.*, *Science*, *302*, 1969, (**2003**)

Photosynthetic Bacteria



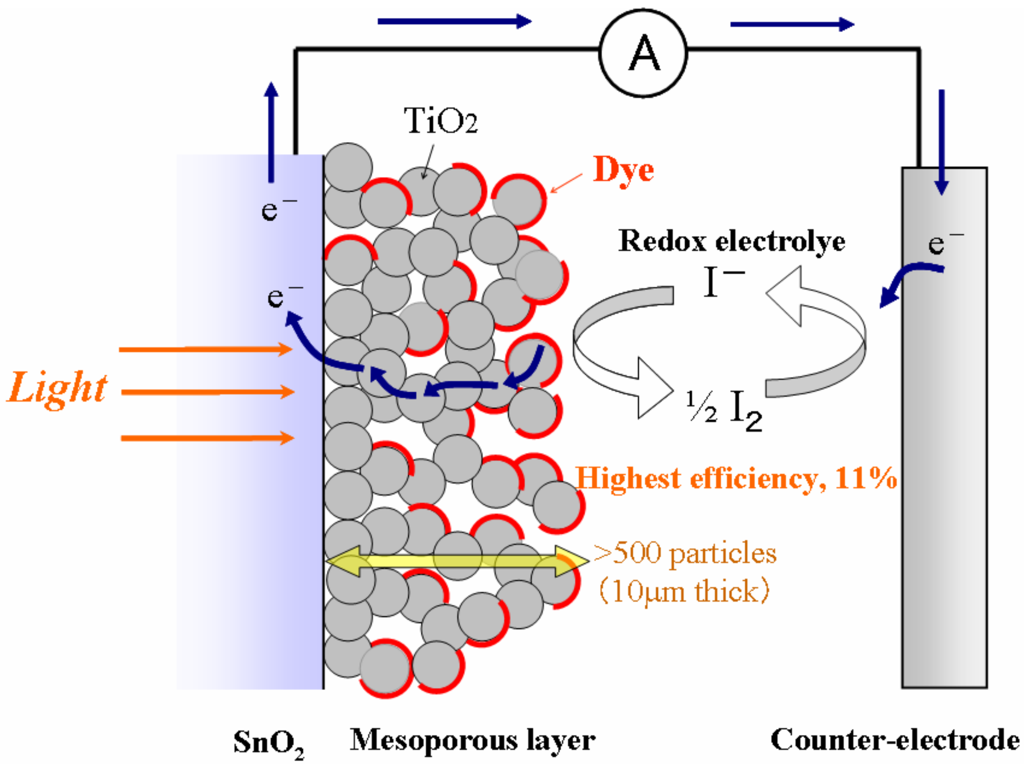
The antenna complexes efficiently realize various photosynthetic functions due to the presence of cofactors (BChl *a* and carotenoid) assembled into the apoproteins.

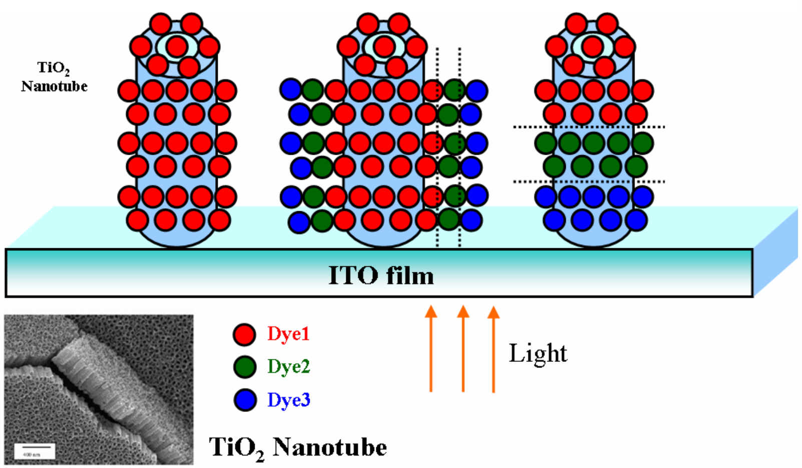


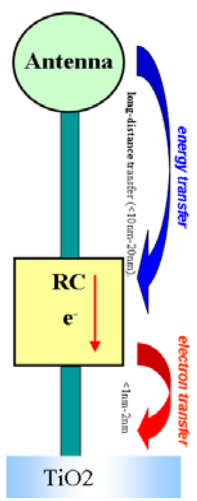


AFM image of the LH1 complex on mica.

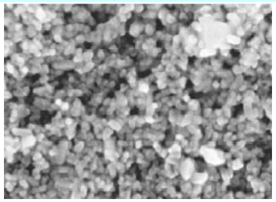
Bio-inspired Design of Dye-sensitized Solar Cell (DSSC)



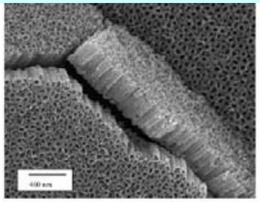




TiO_2

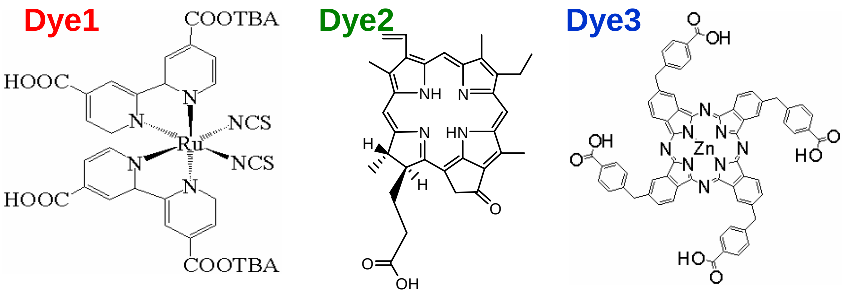


Nano particles



Nanotube

Dye



Ru complex | Chlorophyll | Phthalocyanine

Redox, Electrolyte

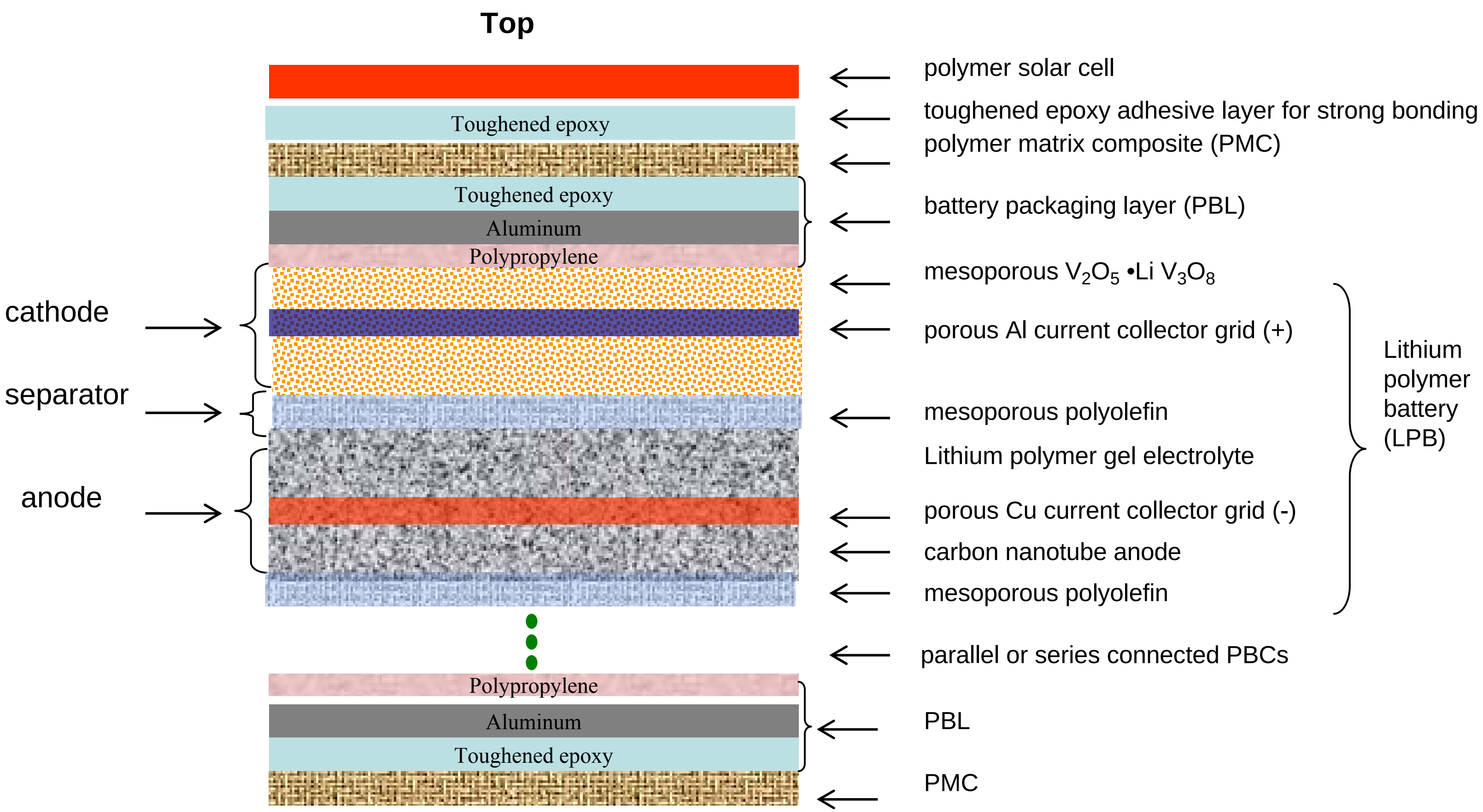
LiI, CuI, KI,Ionic liquids,Solid Electrolyte

Counter

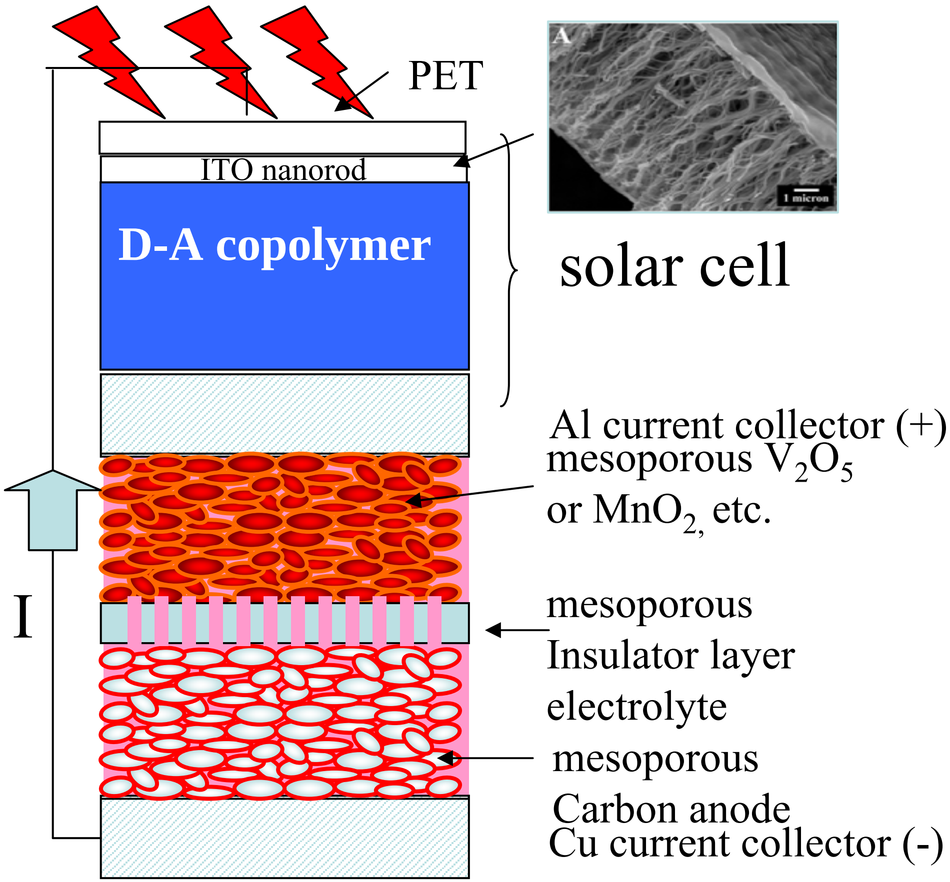
Pt, Au, C60, Carbon nanotube
Film (PET, PEN)

Energy harvesting and storage system

-Development of efficient electrode and electrolyte for battery, supercapacitor and dye-sensitized solar cells



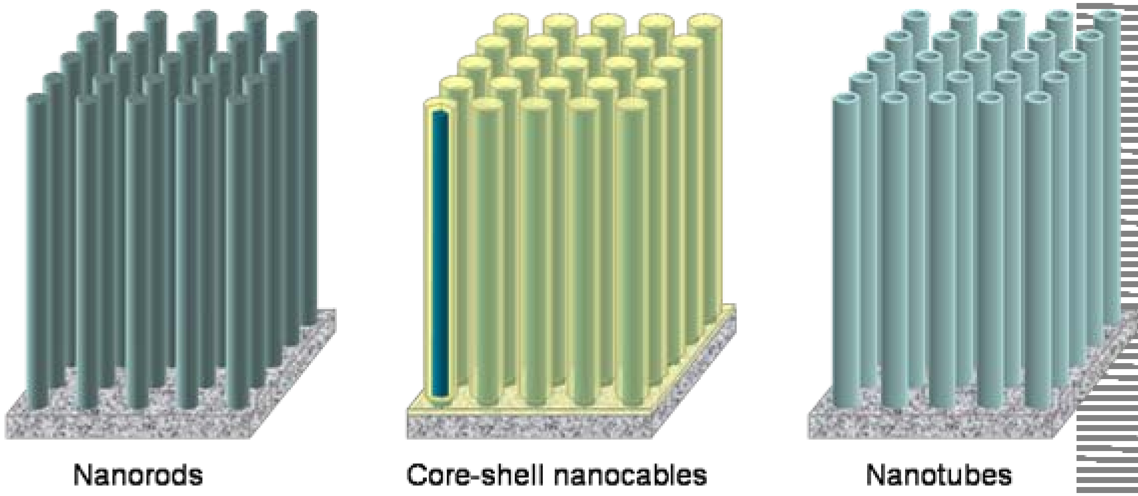
Development of thin film lithium battery for energy storage from polymer solar cell

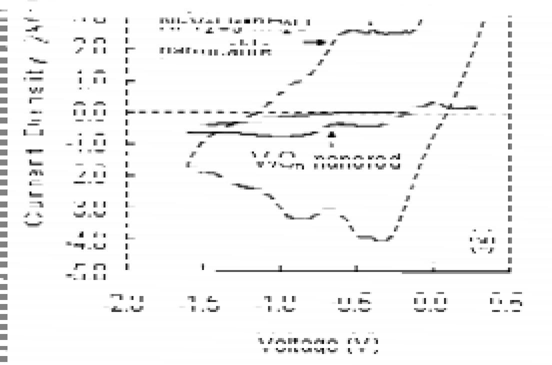


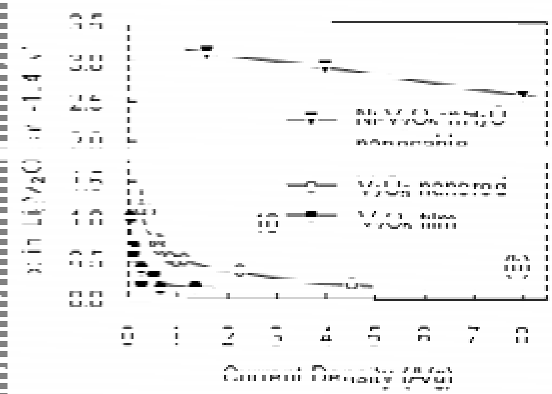
External Quantum Efficiency of Solar Cell	5-10%
Wing area of UAV	10.9 m^2
Solar Energy at 50000 ft	~20 $kWhm^2/day$
PSV harvested Electrical Energy	21.8 kWh/day
Battery Weight to store 2/3 of the energy for night fly	23.8 kg

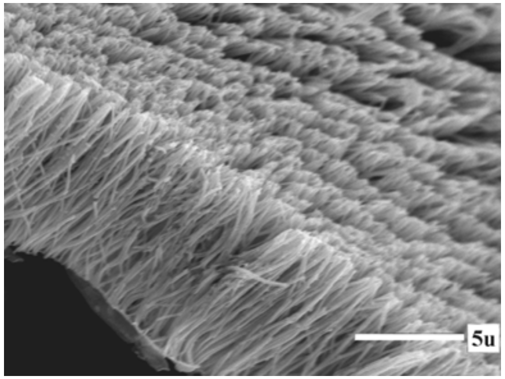
Battery goal: 600 Wh/kg

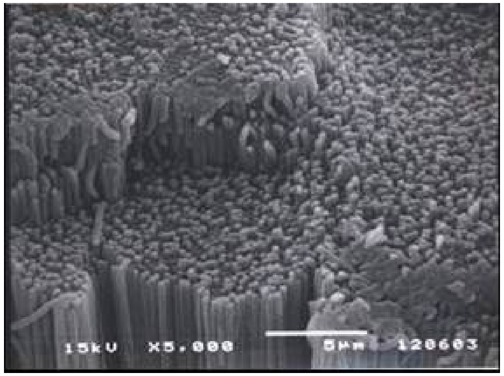
Cao's research 1: Nanostructured Li battery electrodes







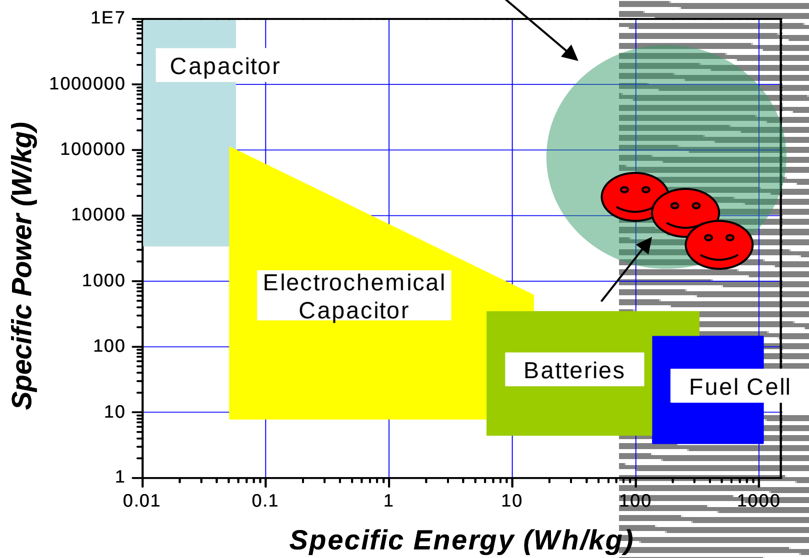


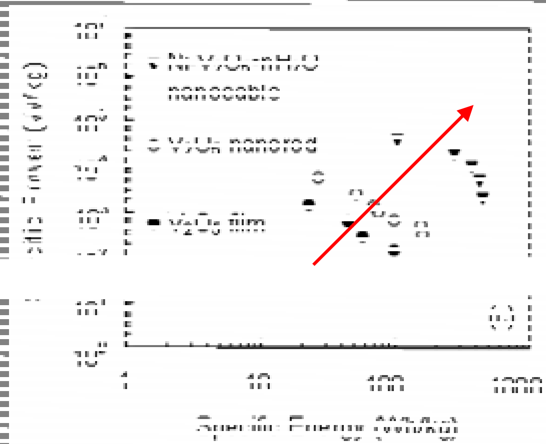


Ideal performance:

Large storage capacity: energy

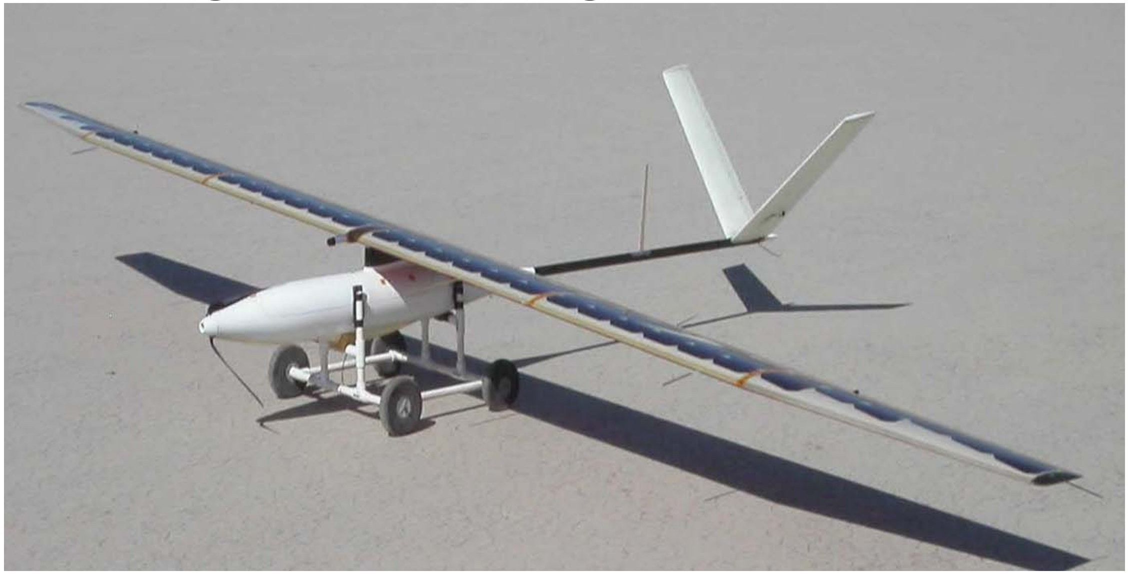
Fast transport kinetics: power





UCLA Task

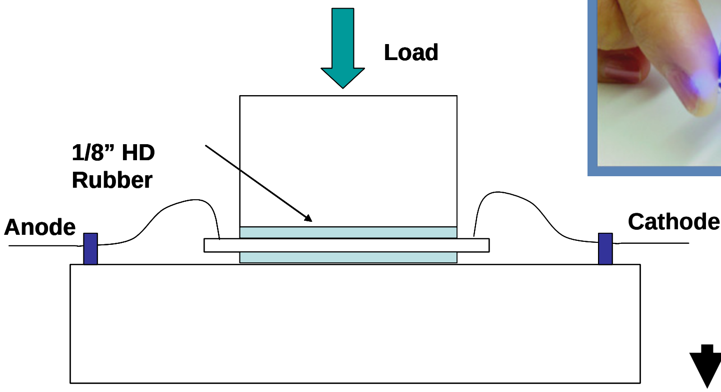
- Goal
  - Develop multifunctional design and manufacturing methodologies for energy harvesting and storage structures.

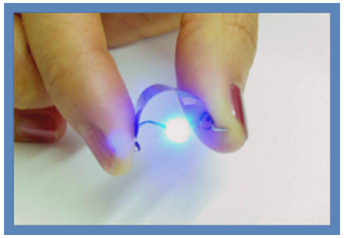


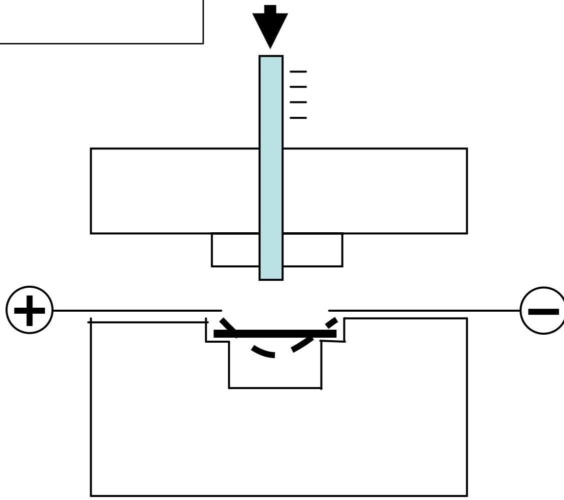
AC Propulsion's SoLong UAV

Multifunctional Characterization of Batteries and Thermoelectrics

- Mechanical Properties
  - Modulus, strength
  - Stress-strain relations
  - Failure mechanisms
- Interaction Between Performance and:
  - Deformation
  - Pressure
  - Temperature

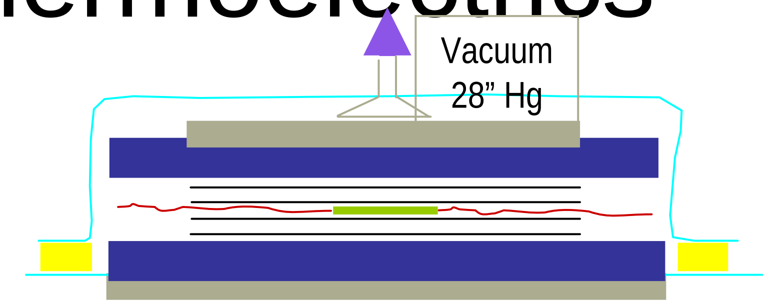


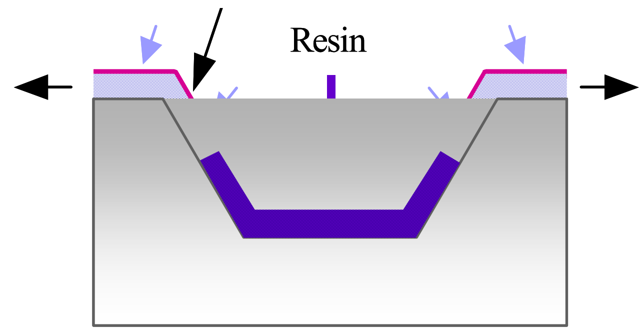


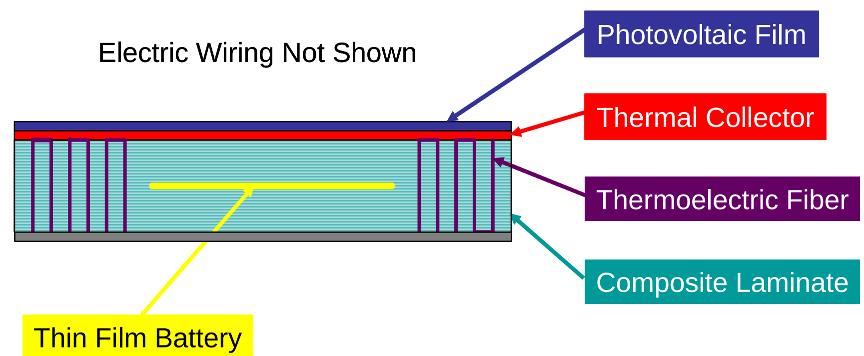


Structural Integration of Batteries and Thermoelectrics

- Structural integration methods
  - Prepreg lay-up
  - Resin transfer molding
- Performance of integrated structures
  - Performance under loading
  - Microstructure analysis

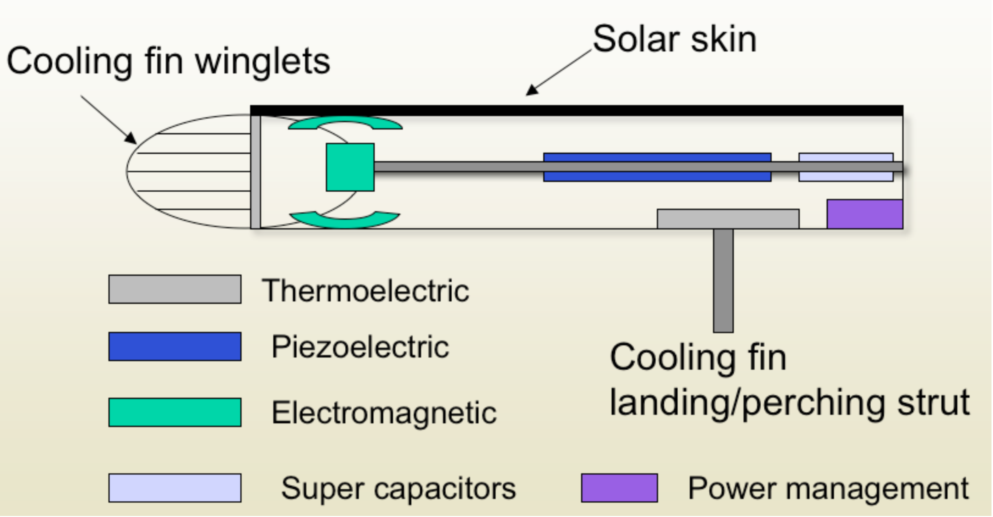






Design Rules for Multimode Harvesting

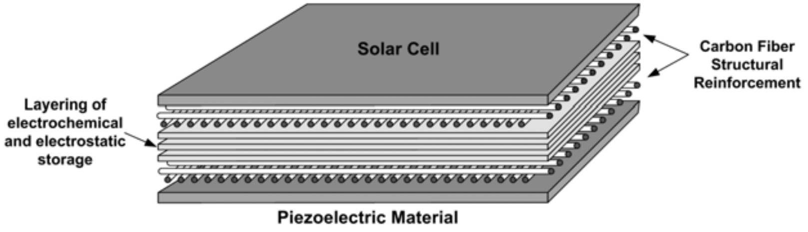
- Tasks included determining:
  - Available sources
  - Placement criteria
  - Key parameters
  - Design rules
  - Storage and power management
  - Experimental verification
  - Transitions to DOD



MAV Wing Cross Section

Formulate analysis tools for hybrid harvesting and storage

D. J. Inman



H A Sodano

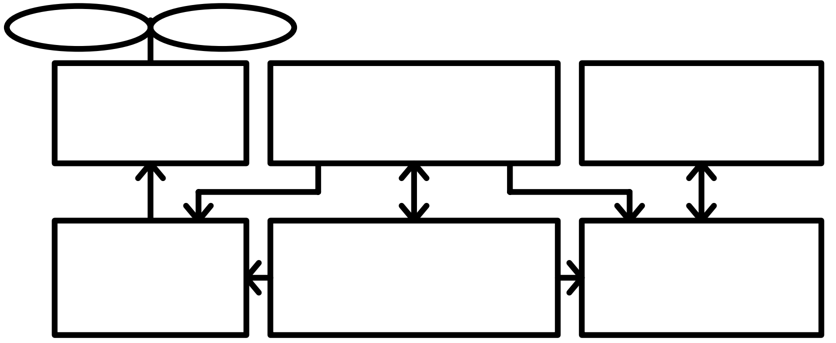
Electric System Design Using Supercapacitors and Battery

Goals

-Integration of energy harvesting devices into electrical system.

-Study of energy efficiency and how to improve it.

-Initial design will be conducted with currently available energy harvesting devices including thermoelectric devices, photo-cells and super-capacitors.



Simplified diagram of the electrical system






MURI Collaboration Team