Electroactive polymers

Three main kinds of materials

metals, plastics and ceramics.

Preface

I am inclined to think that the development of polymerization is, perhaps, the biggest thing chemistry has done, where it has had the biggest effect on everyday life. The world would be a totally different place without artificial fibers, plastics, elastomers etc. Even in the field of electronics, what would you do without insulation? And there you come back to polymers again.--- *Lord Todd, president of the Royal Society of London, quoted in Chem. Eng. News* ***58*** *(40), 29 (1980), in answer to the question, What do you think has being chemistry's biggest contribution to science, to society?*

From clothing to the artificial heart, polymers touch our lives as do no other class of materials, with no end in sight for new uses and improved products.

Polymer

Macromolecule

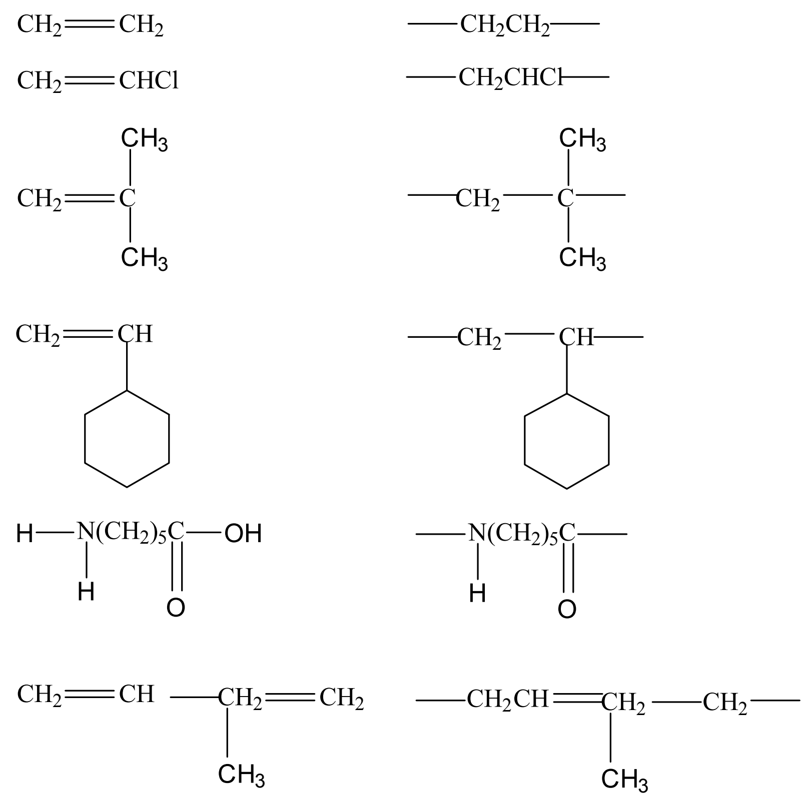
Out line of the science of large molecules

- Polymers
  - Biological materials → Plant fiber, starch saccharin etc.
  - Nonbiological materials
    - → Plastics fibers, elastomers
    - → Rubber, wool, cellulose, silk and leather etc.

Some linear high polymer, their monomers, and their repeat units

Polymer | Monomer | Repeat Unit

- Polyethylene
- Poly(vinyl chloride)
- Polyisobutylene
- Polystyrene
- Polycaprolactam (6-nylon)
- Polyisoprene (natural rubber)



Polymerization

- Step-reaction (Condensation) polymerization
- Radical chain (addition) polymerization
- Ionic and coordination chain (addition) polymerization
- Copolymerization

Characterization for Analysis and Testing of Polymers

-----Common Methods and Equipments

- Dynamic light scattering spectrometer- thermodynamics properties
- Mass spectrometry- structure of low-molecular- weight species
- Infrared Spectroscopy (IR) - structure
- Nuclear Magnetic Resonance Spectroscopy ^{1}HNMR and ^{13}CNMR -chain configuration, sequence distribution, and microstructure
- X-ray diffraction analysis WAXD- the spatial arrangements of the atoms
  SAXS: larger periodicities
- Light Microscopy (SALS)- spherulites or rod and phase-contrast
- Electron Microscopy and Electron Diffraction
- Scanning Electron Microscopy (SEM) and Transmission Electron Micrograph (TEM)
- Deferential Scanning Calorimetry (DSC)- thermal analysis
- Stress-strain properties in Tension

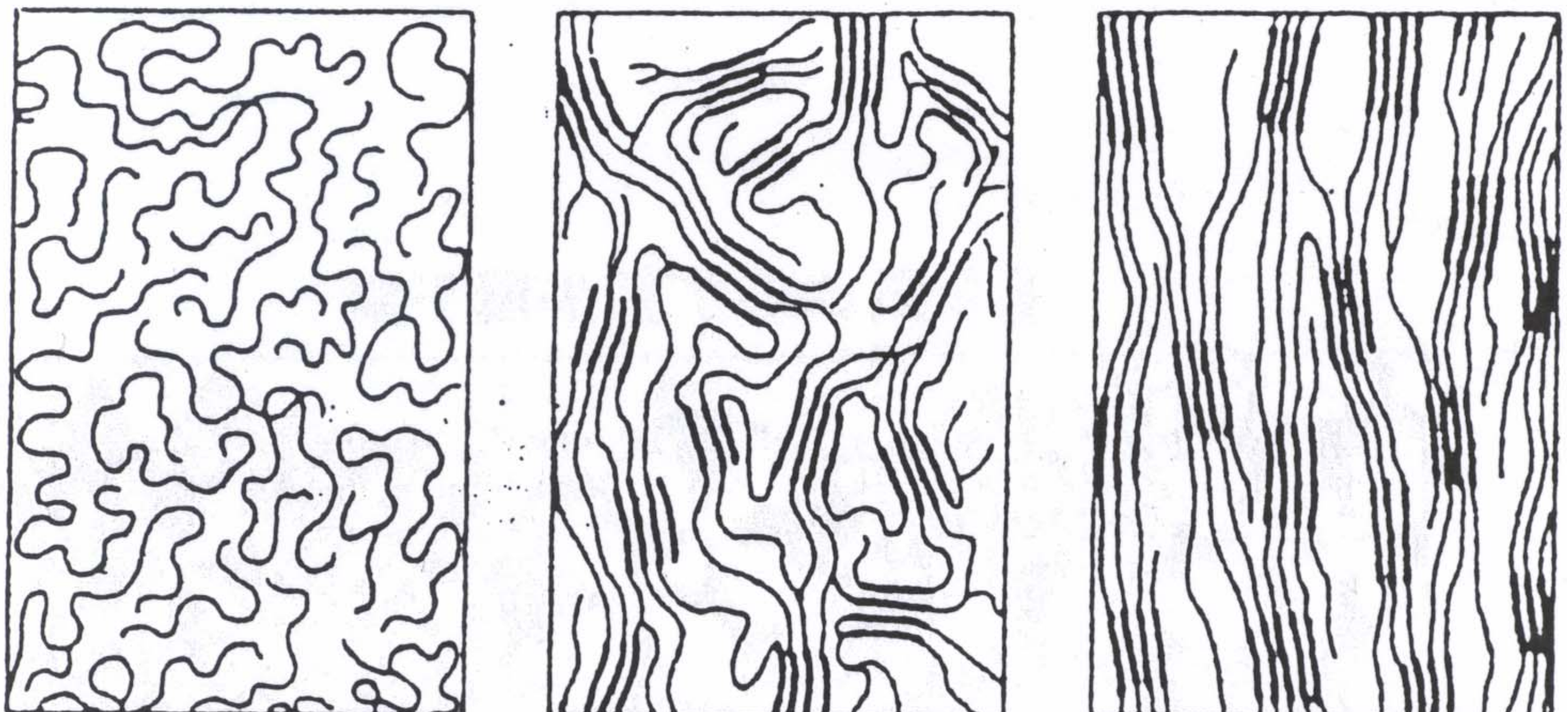
States of Polymer

Polymers

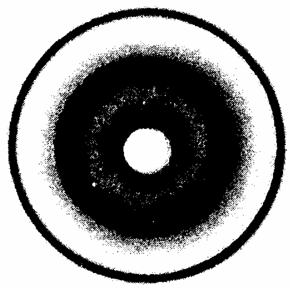
- liquid states
  - → **Biological field**
  - → how to make gel, film, fiber and composite etc.
- sol- gel states
  - → artificial muscle, switch and smart window etc.
- solid states
  - → film, fiber and container etc.

    artificial muscle, switch and smart window etc.

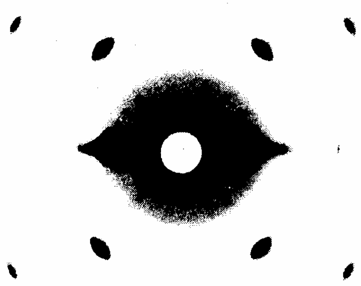
Solid structure of Polymer



Amorphous rubber | Random crystalline plastic | oriented crystalline fiber



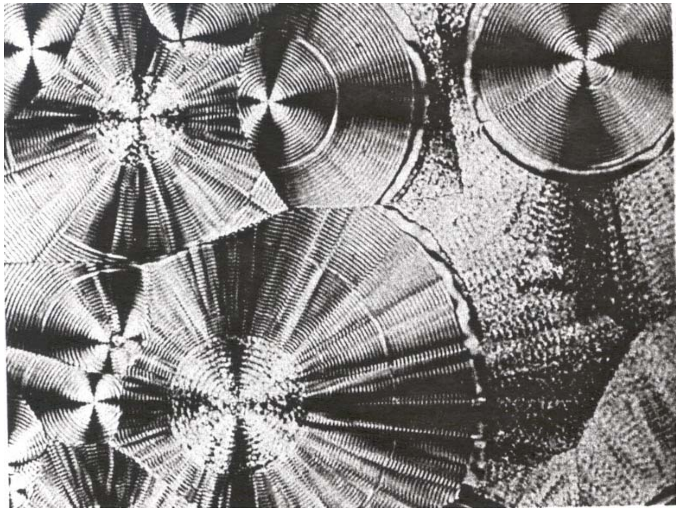
(a)



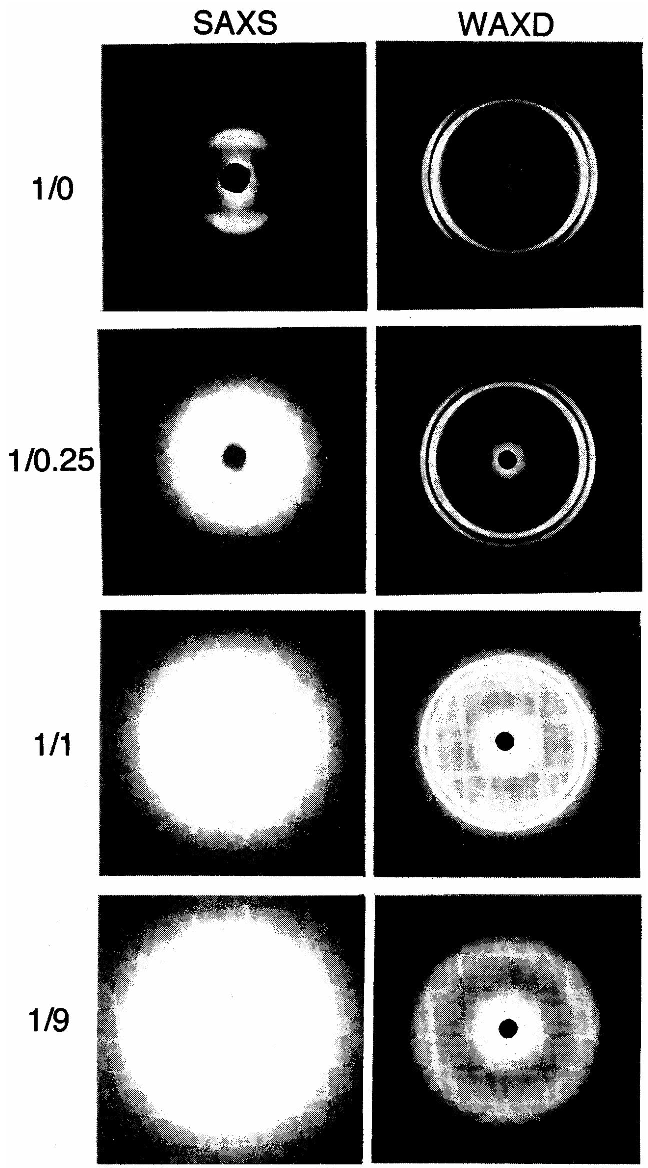
(b)

X-ray diffraction patterns for unoriented (a) and oriented (b) polyoxymethylene (courtesy of E.S. Clark)

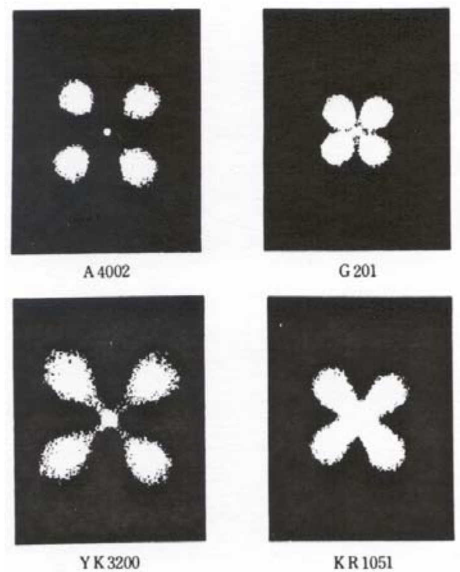
Ringed spherulites of poly(trimethylene glutarate) observed in the optical microscope between crossed polarizers (Keller 1959)



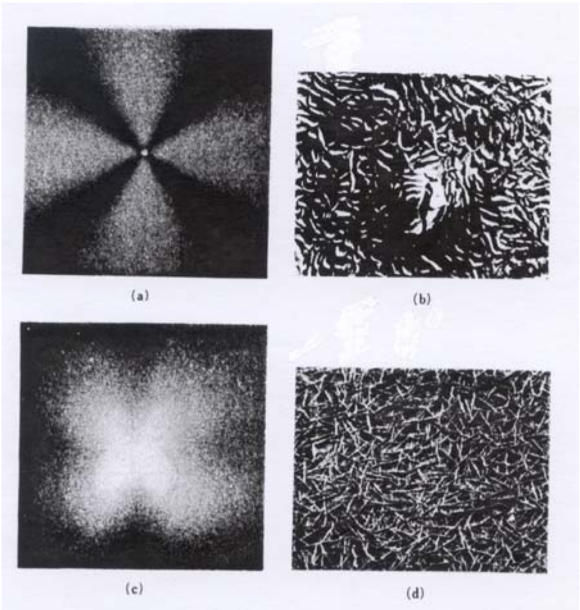
Electro micrograph of a portion of a ringed spherulite in linear polyethylene (photograph by E.W. Fischer, from Geil 1963)



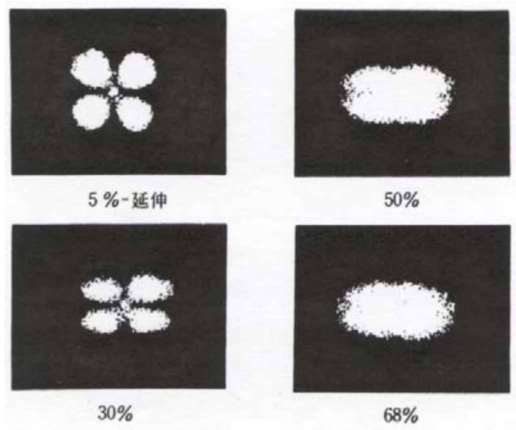
SAXS and WAXD patterns (end view) from polyethylene/carbon blend materials with the indicated compositions



(a) H_v SALS photos of low and medium density polyethylene



(c) Surface replica electron microscopy of Polytetrafluoroethylene (Teflon) with different heat treatments (b) and (d) and corresponding with Hv SALS (a), (c)



(b) Hv SALS photos with indicated draw ratios (stretching direction is vertical)

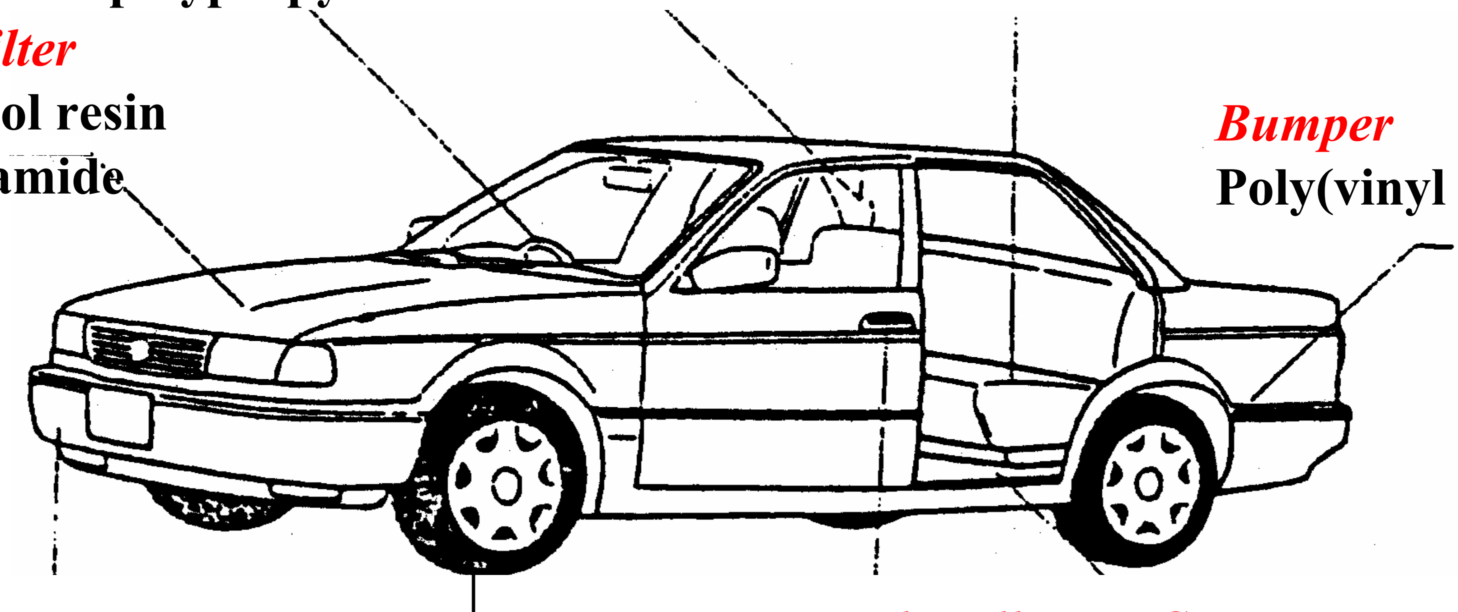
Utilizing plastics for car components

Handle
Poly(vinyl chloride)
polypropylene

Proof , Seat
Poly(vinyl chloride)

Air filter
Phenol resin
Polyamide

Bumper
Poly(vinyl chloride)



Bumper
Polypropylene
Polycarbonate

Tire
Synthetic resin
(styrene)

Door handle
Polycarbonate
Polyacetal

Carpet
Nylon

Active materials

sensing and responding to change of environment

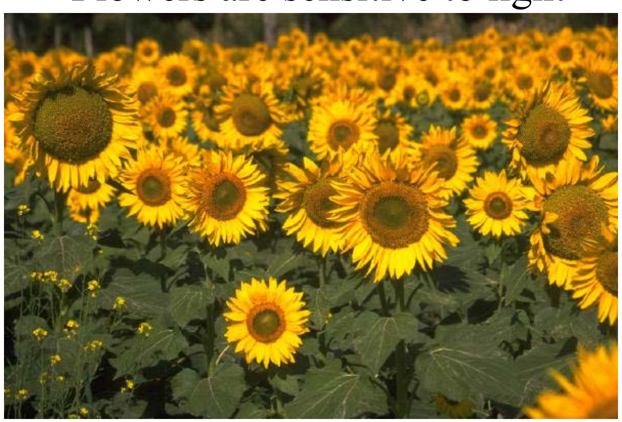
<u>Environmental stimuli</u>

- Temperature
- Solvent, pH
- Electric field
- Magnetic field
- Light or UV

<u>Response</u>

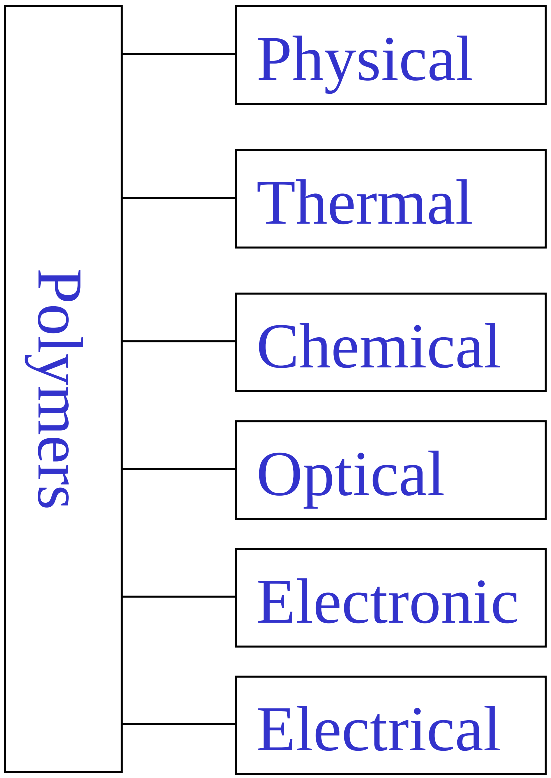
- Phase
- Shape
- Optics
- Mechanics
- Permeation rates
- Recognition

Flowers are sensitive to light



This fish changes color according to the surroundings

Polymers with electrical and electronic properties



Conventional polymers (using their strength, flexibility, elasticity, stability, mould ability, dielectric properties, etc.)

Specialty polymers

(using their electrical conductivity, photoconductivity, nonlinear optical effects, dielectric properties, etc.)

Electroactive Polymer (EAP) Materials

- **Electric EAP**

--- PVDF-based Ferroelectric polymers

- **Ionic EAP**

---Electroactive polymer gels
---Ionomeric Polymer-Metal Composites

- **Non-ionic EAP**

--- PVA-based

- **Carbon nanotube Actuator**

- **Conductive Polymer**

---PPy and PANI
--- PEDOT and PEDOP based

Applications and application potentials

- **Antenna and mirror**

- **Biomimetics and switching technologies**

---Nafion, Flemion, poly(vinyl alcohol) (PVA) gel, conducting polymer and carbon nanotube actuator

- **Switching window, electromagnetic shutter and display technologies**

--Acrylamide and vinyl derivative copolymer, copoly(Aam/vdMG) gel and electrochromic polymer, ProDOT-(CH_3)

- **Drug delivery system**

--- Polymer gel and Conducting polymer:
e.g. polyacrylamide gel polypyrrole(PPy)

- **Sensor**

Nafion and polyaniline (PANI)

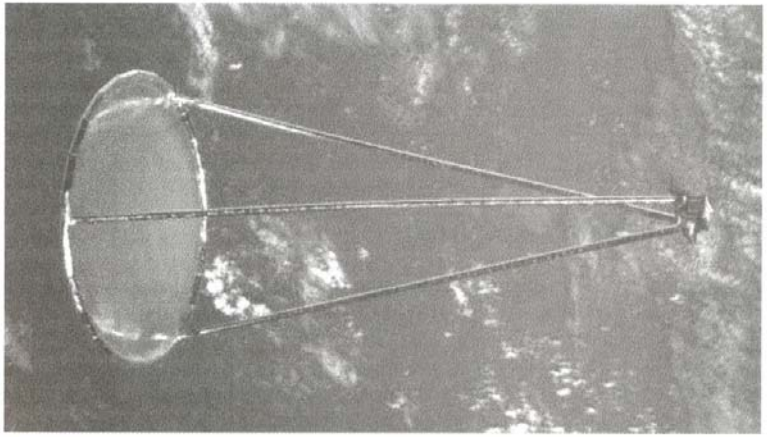
Applications

Comparison of energy storage capabilities of several dielectric materials and capacitors technologies

Dielectric Material	Dielectric Constant	Applied Electric Field (MV/cm)	Energy Density* (J/cm^3)	Comments
Polyethylene	3.2	4.0	2.3	
Polyester	3.4	4.0	2.5	
PVDF	12.0	2.5	3.3	Ferroelectric
PVDF+$BaTiO_3$ Composite	40.0	1.6	4.5	40 vol% $BaTiO_3$ Powder
Al_2O_3	9.0	3.0	3.6	
Ta_2O_3	26.0	2.0	4.6	
Diamond	7.8	7-10	16-24	Unproved
Electrolytic Theoretical Packaged	 --- 1000's μFarads	 --- 450 Volts max.	 20-30 1	 Slow Discharge
Ultracapacitors	1000's Farads	2.5 Volts max.	10-15	Slow Discharge
$PbZrO_3$	>20,000 @ Phase Change	~ 0.5 (< ½ DBS)	18	Single Crystal Antiferroelectric
Ceramic Antiferroelectric	>4000 @ Phase Change	~ 0.5 - 0.8 (< ¾ DBS)	12 (material) 7-10 (capacitor, projected)	Multilayer Capacitor
PVDF-TrFE Irradiated Copolymer	**65**	**3** **5 (projected)**	**12.5** **> 20 (projected)**	**@ Peak Dielectric Temperature**

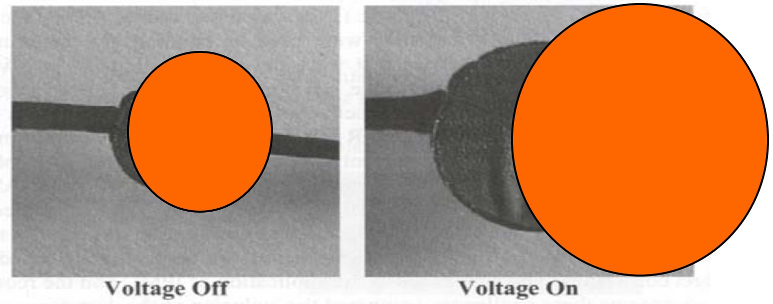
Space mirror…

(a) Echo 1 passive satellite (courtesy NASA).



(b) Inflatable antenna experiment on orbit. The inflatable antenna was packaged into the reusable Spartan satellite seen on the right (courtesy NASA).

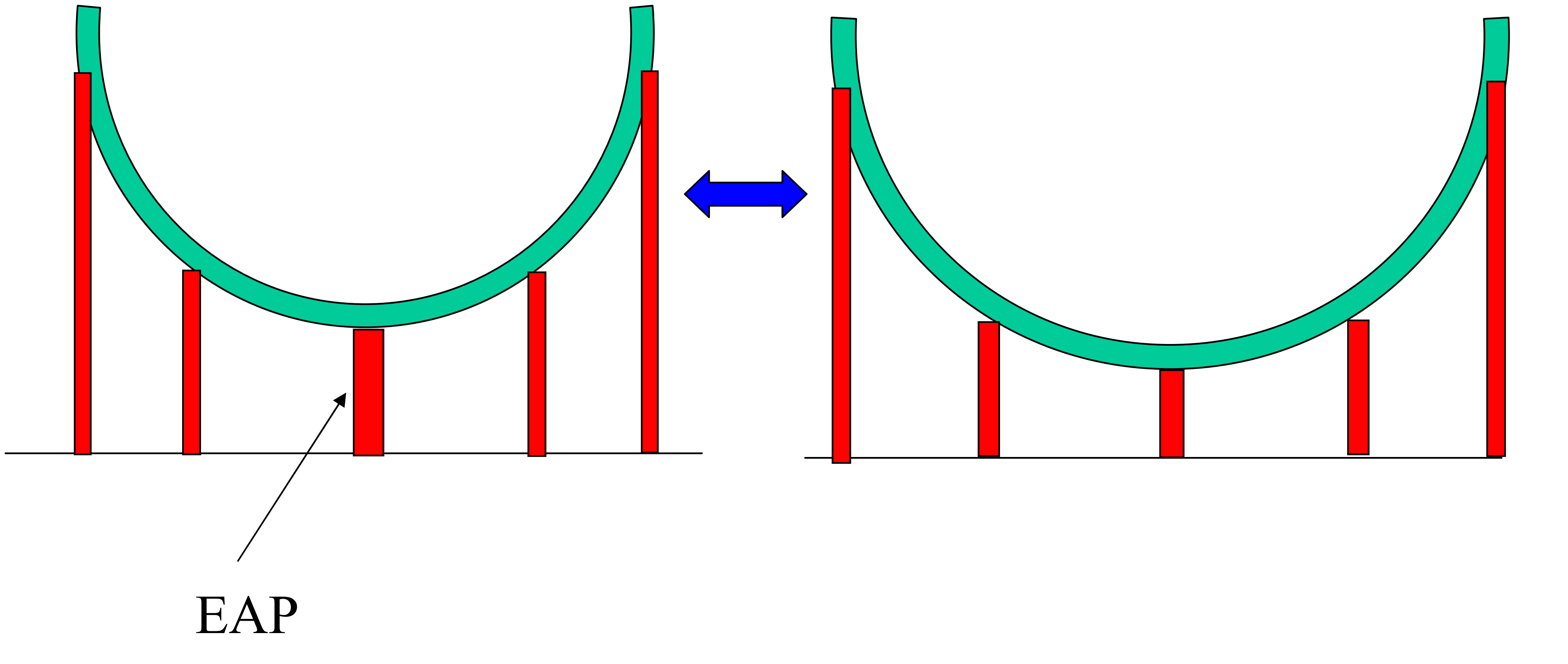
(c) A space shuttle view of the L'Garde's inflatable antenna experiment (IAE).



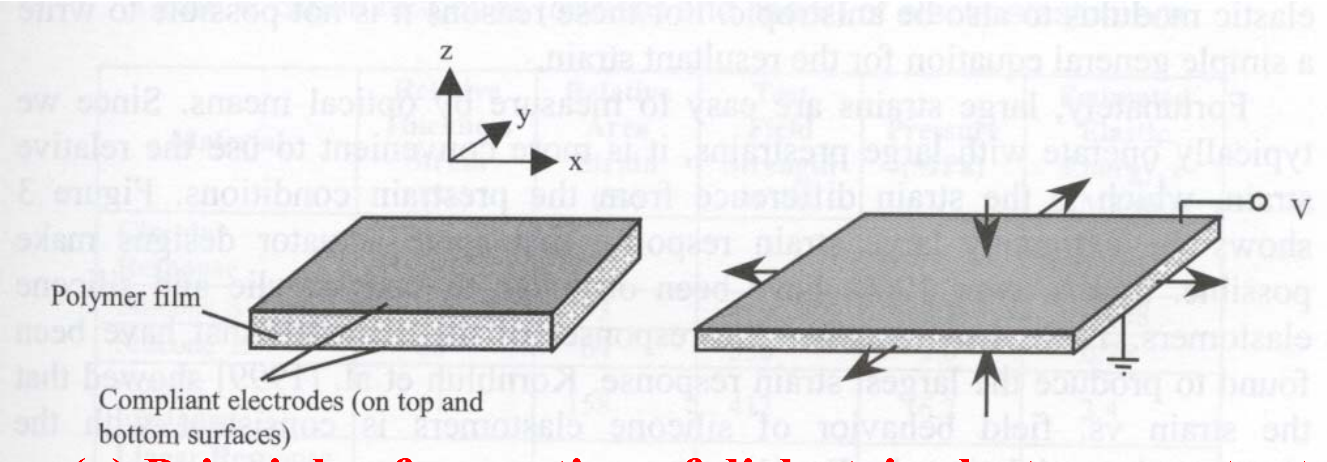
(d) Dielectric actuator demonstrated to expand and relax (courtesy of R.Kornbluh and R.Pelrine, SRI International).

How they work?

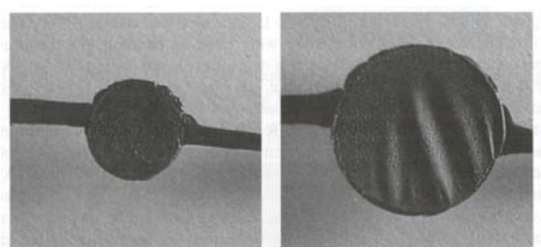
- **Antenna**



How they work?

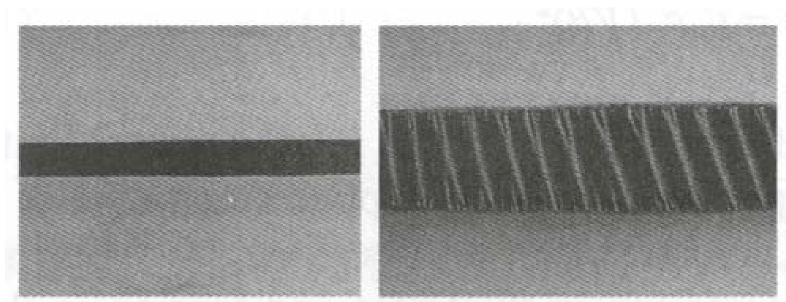


(a) Principle of operation of dielectric elastomer actuators.



voltage off **voltage on**

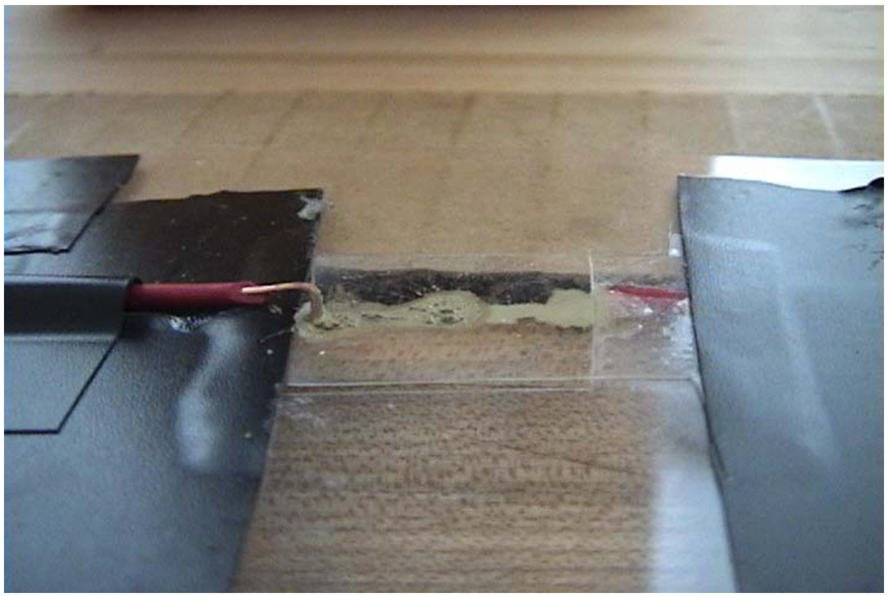
(b) Biaxially uniform prestrain and circular electrodes.

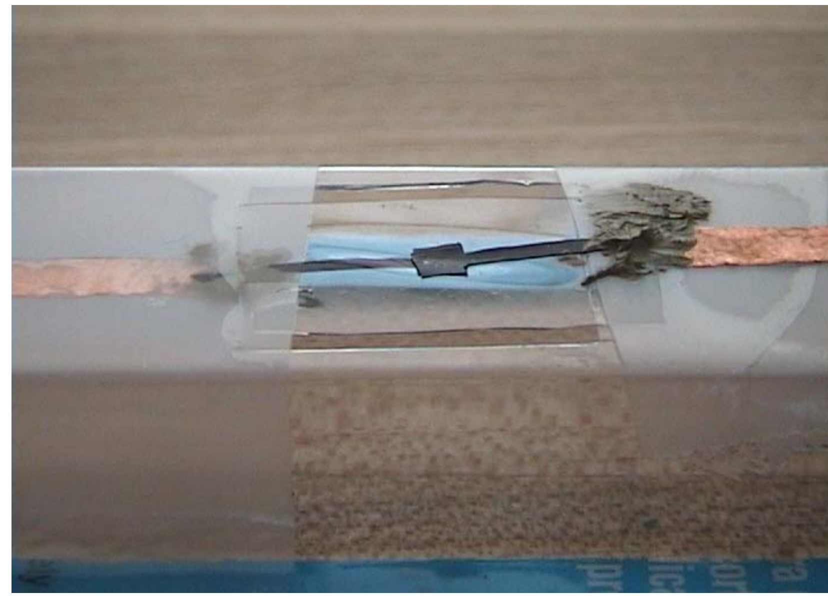


voltage off **voltage on**

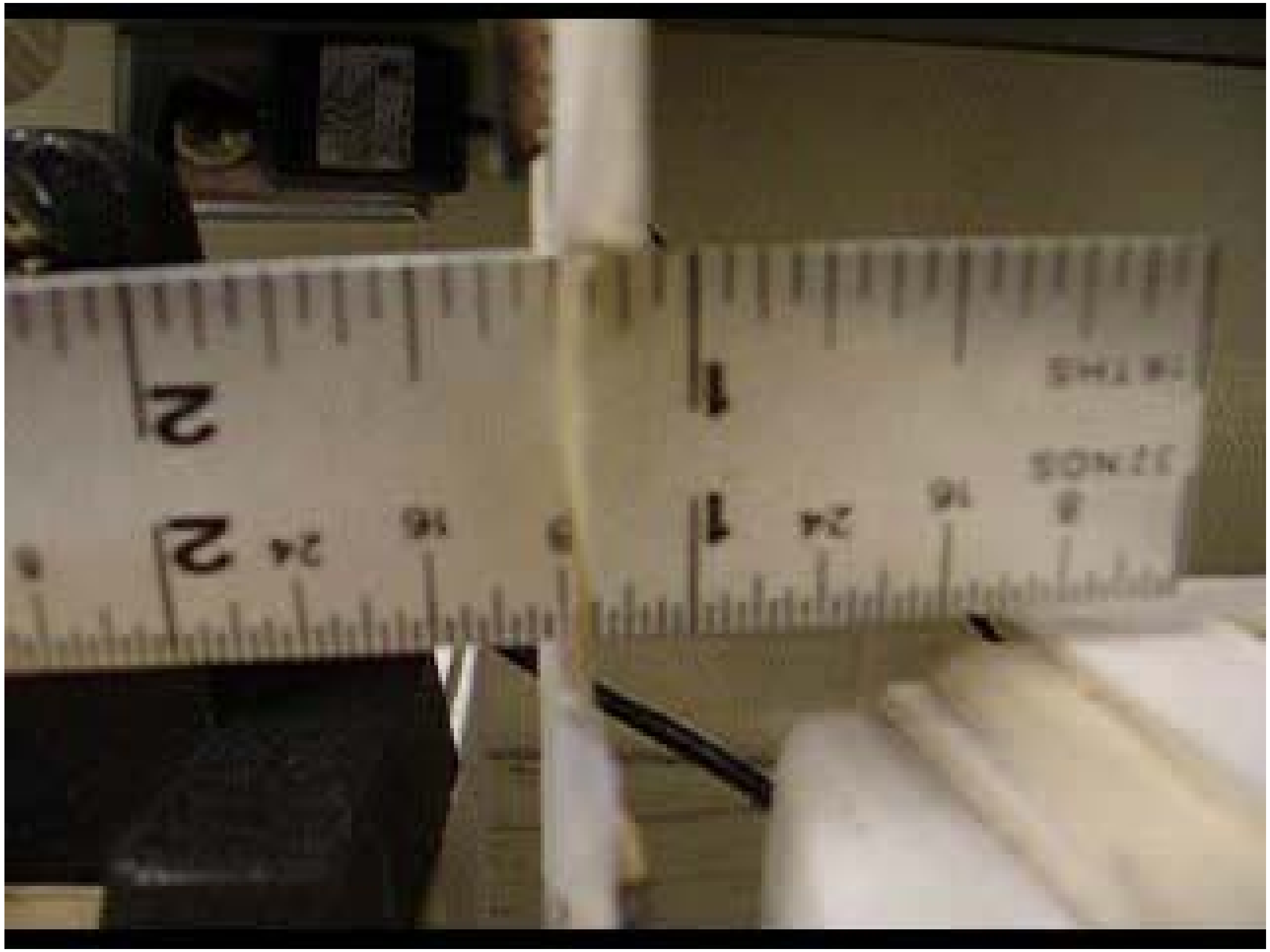
(c) Anisotropic prestrain with linear electrodes.

Dielectric actuator

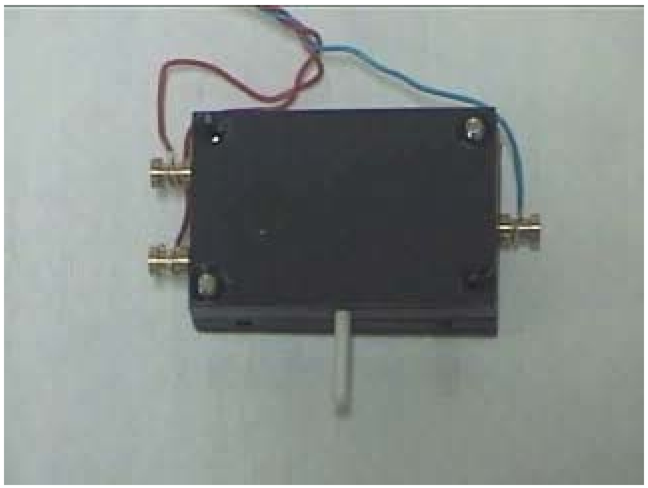


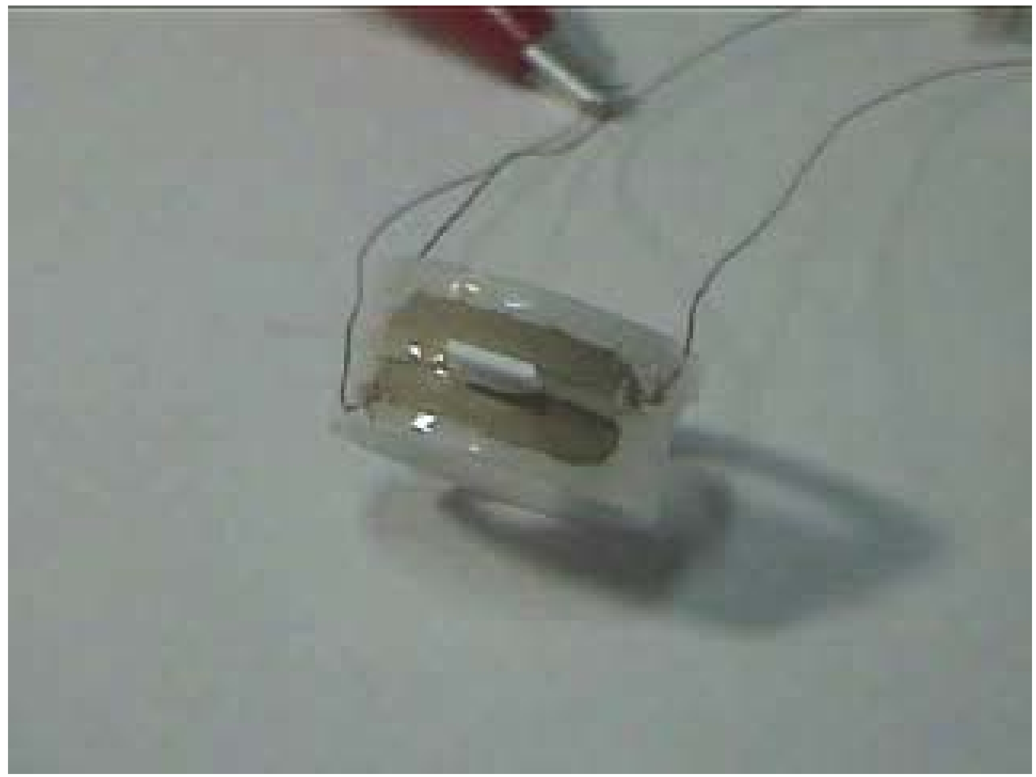


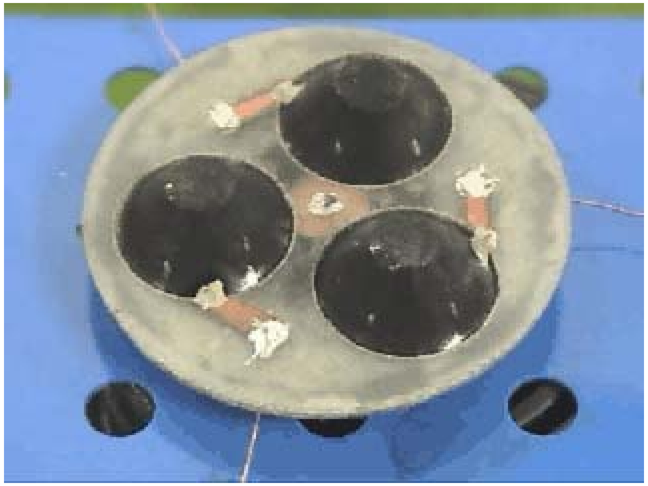
Dielectric actuator



Snake-like actuator

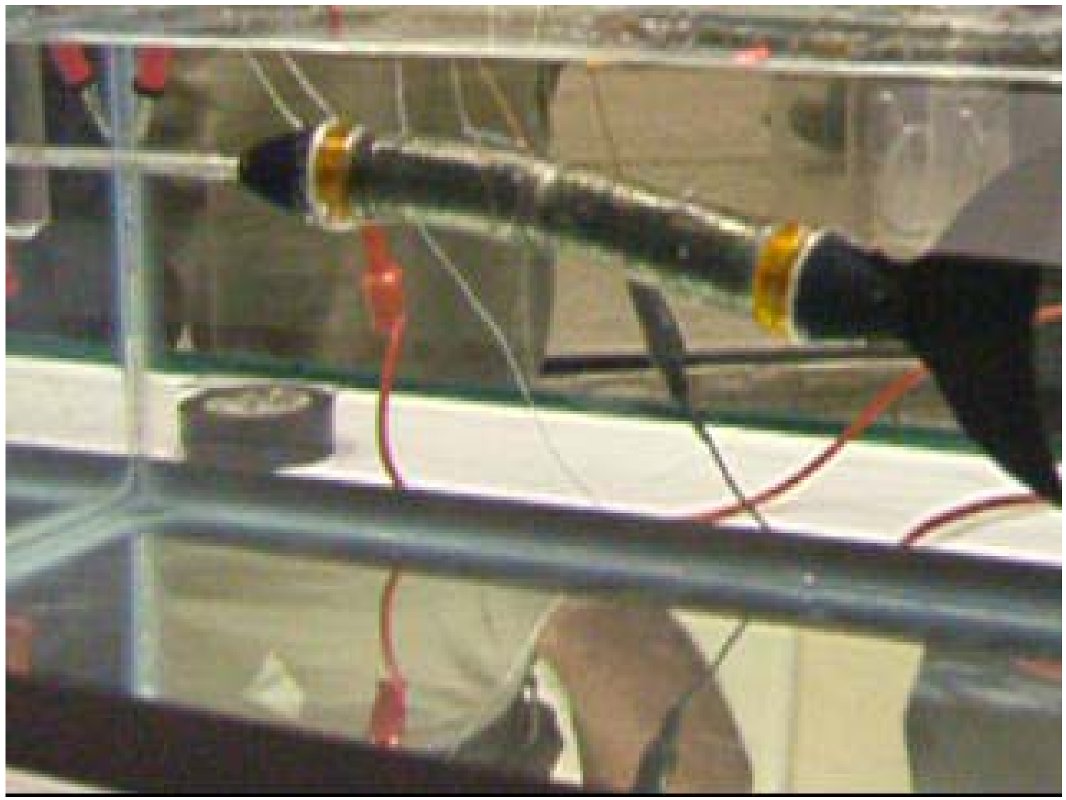






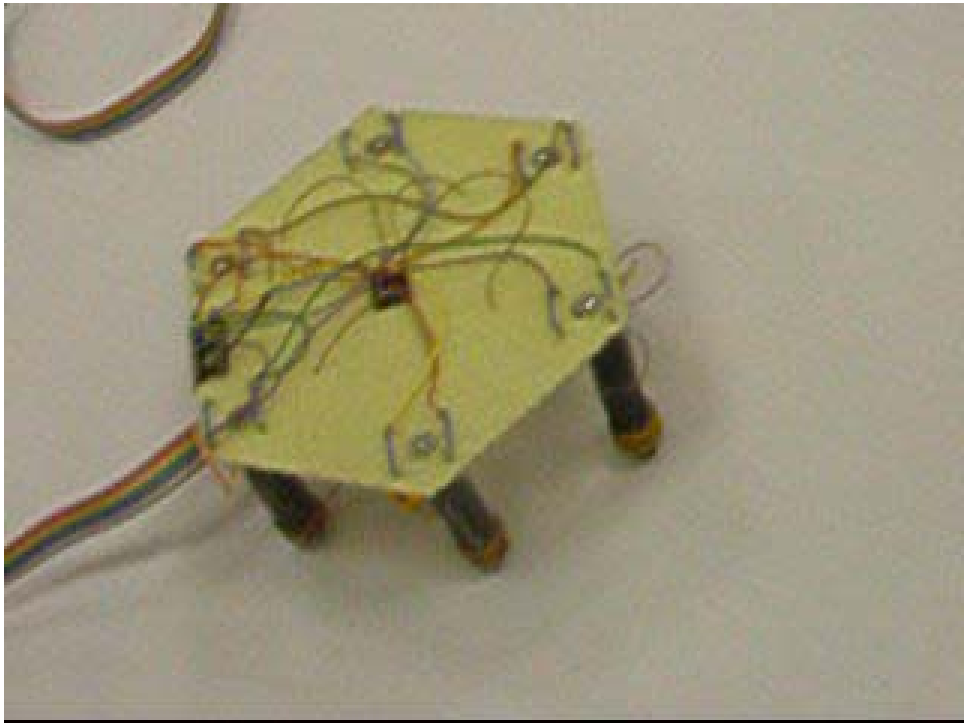
Linear actuator

Fish actuator



SRI

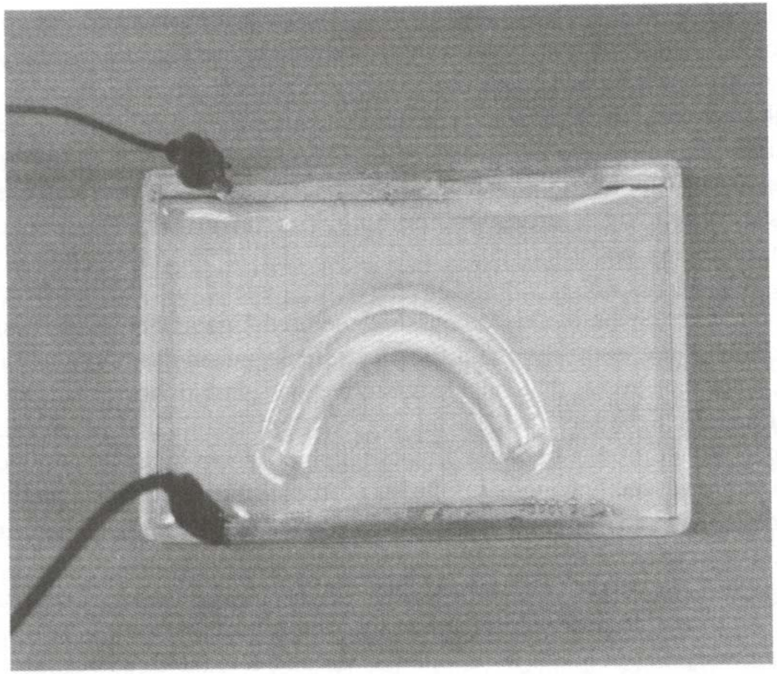
Walking robot



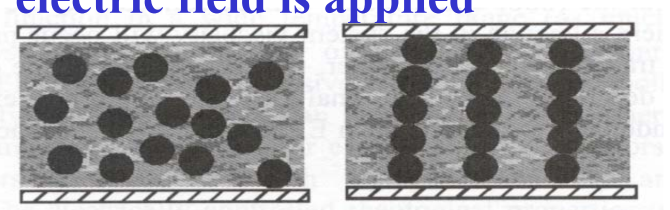
SRI

Animation

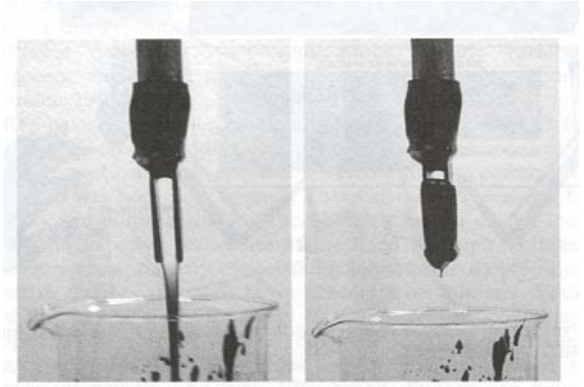
How they work?



(a) Bending of a polyacrylic acid gel rod sodium hydroxide. DC applied field, cathode (negative) at a bottom. Gel swells on the anode side and bends toward the cathode [Shiga, 1997]

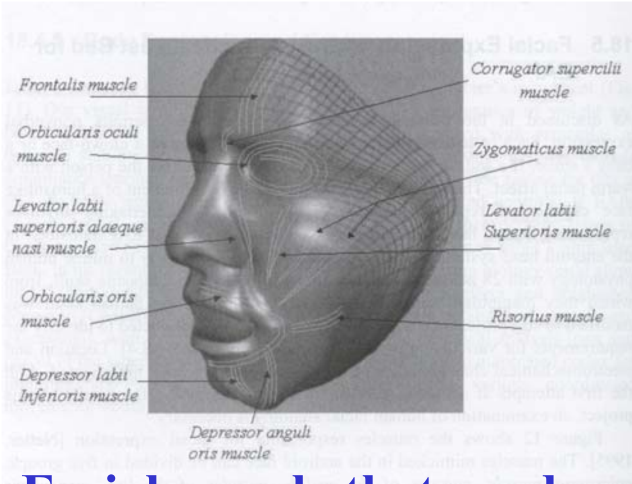


(b) Particle suspension forms chains when electric field is applied

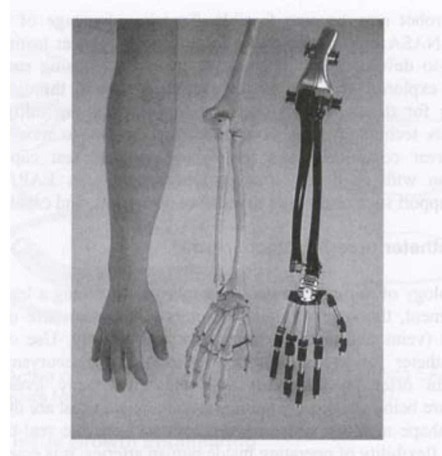


(c) Electrorheological fluid at reference (left) and activated state (right) [courtesy of ER Fluid Developments Ltd, UK]

Applications



(a) Facial muscle that produced expression [Netter, 1995]



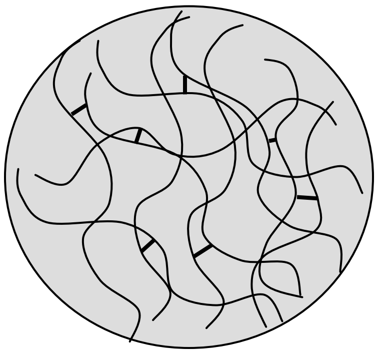
(c) A photographic view of a human hand and skeleton as well as an emulated structure for which EAP actuators are being sought
[Courtesy of Garham Whiteley, Sheffield Hallam University, UK]

(b) Smiling robot of Hidetoshi Akasaw

(d) Dynamic gestural figure with muscles exposed.

How they work?

Polymer Gels



Gel structure:
- Solid phase - crosslinked polymer matrix
- Liquid phase - solvent

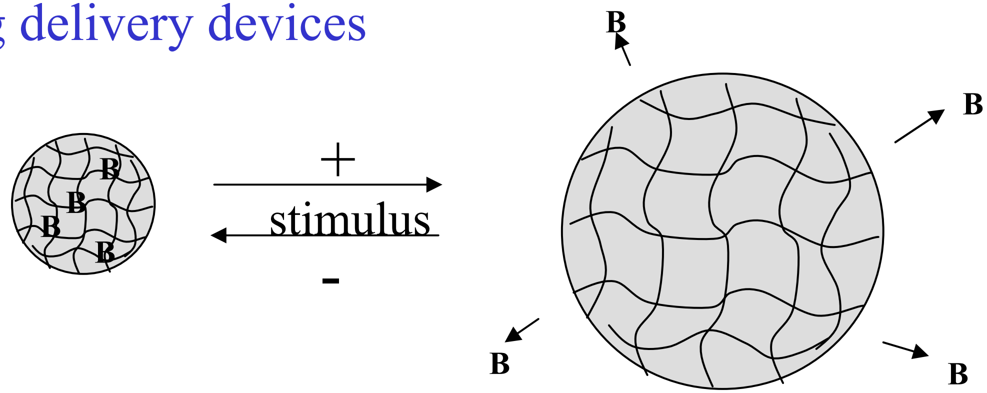
Phase transition - discontinuous change of properties, size, shape, etc. under discrete change of environment

Molecular interactions - ionic, hydrophobic, hydrogen bonding, van der Waals

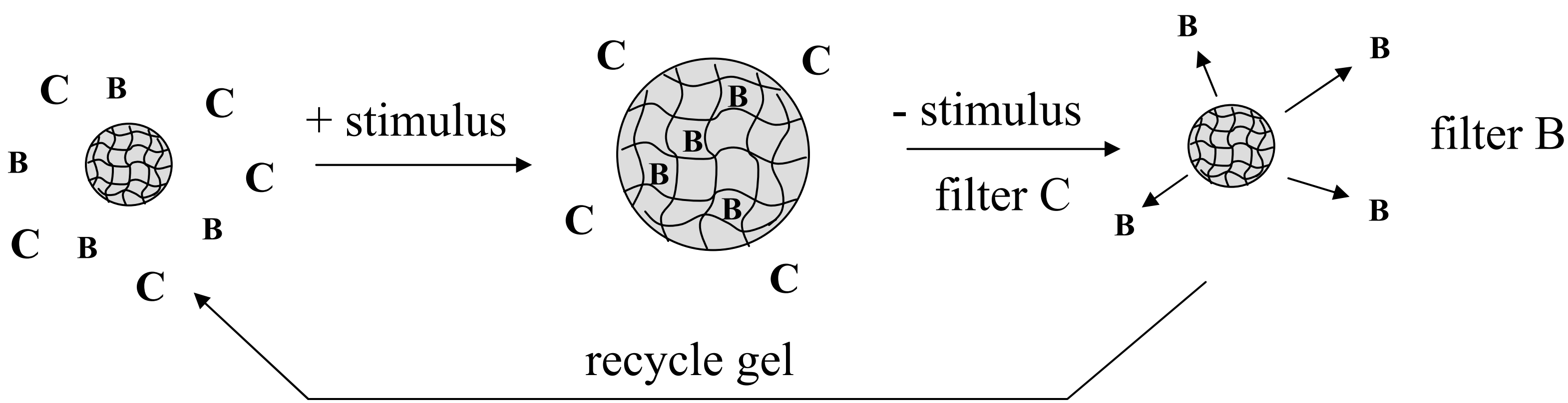
How they work?

Current applications: Medicine and Biotechnology

1) Drug delivery devices



2) Molecular separations



Study on several EAPs

(1) Poly(vinyl alcohol) (PVA) gel

(2) Nafion and Flemion

(3) Copoly(Aam/vdMG) gel

(4) Electrochromic polymer, ProDOT-(CH_3)

Material development

- **Polyvinyl alcohol (PVA) gel:**

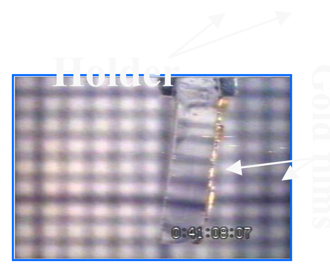
  - actuation in electric field by contraction and bending

  - influence of structure to deformation:
    - molecular level
    - macroscopic level

  - fastest response (<1s)

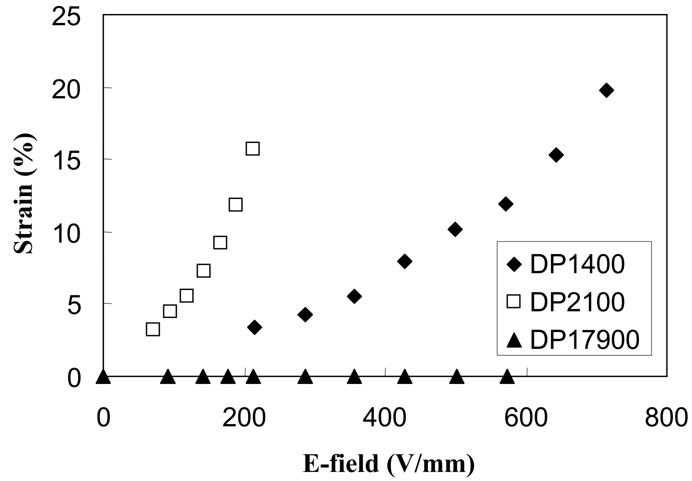
  - low strength material

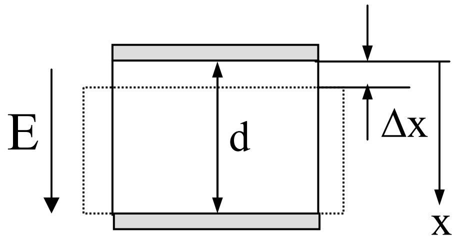
  - high applicable voltage



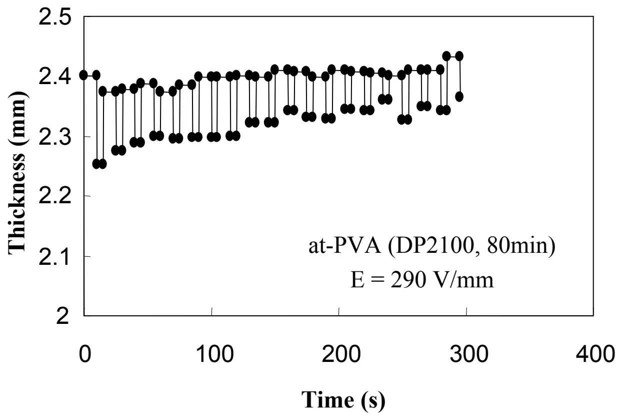
Influence of structure - molecular level

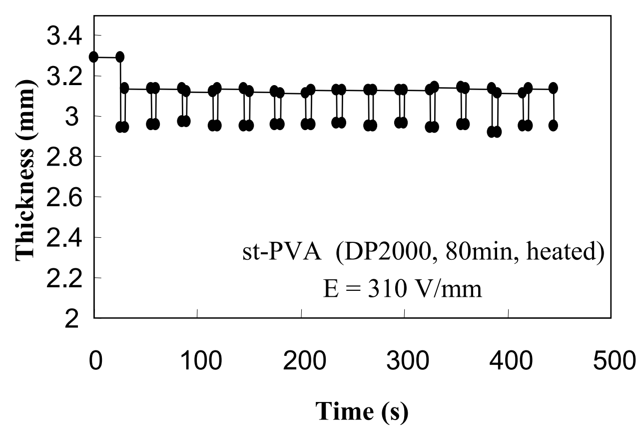
- Degree of polymerization (DP) - 1400, 2100, 17900



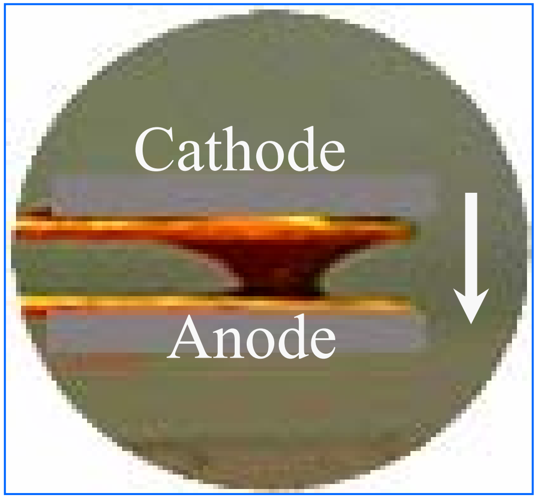


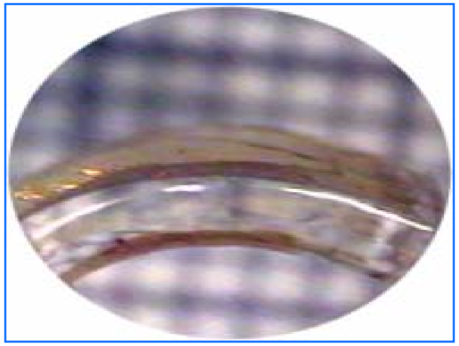
- Tacticity - atactic, syndiotactic

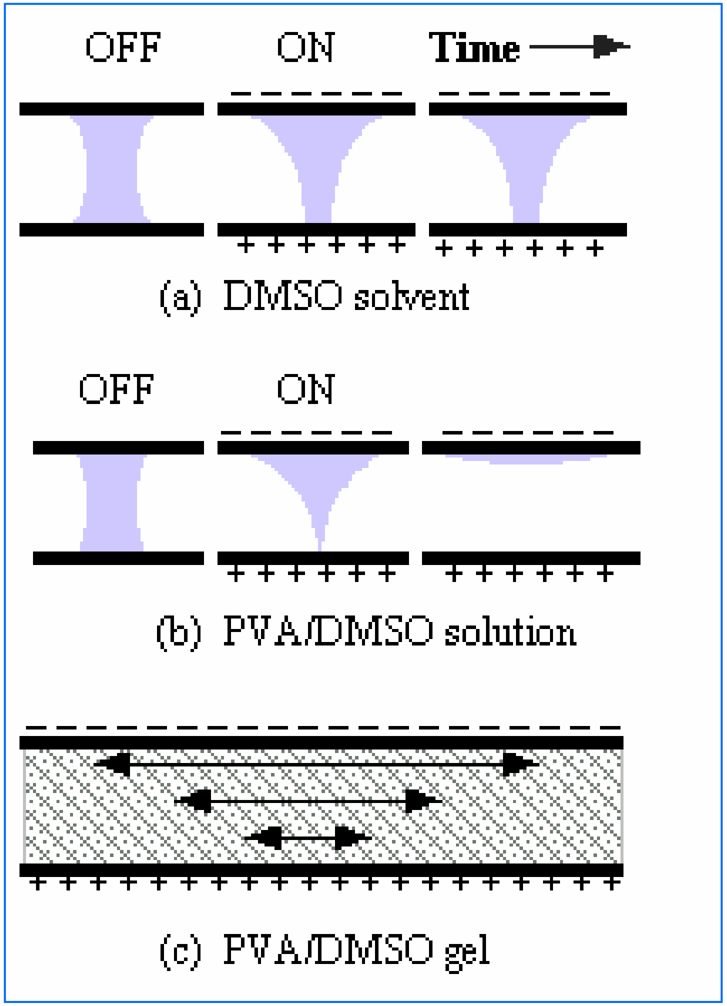




Stress Generation







Mechanism of Electric Actuation

- Dielectric liquid can be ionized upon high E-field

$$j = \rho \cdot b \cdot E = \frac{I}{A}$$

$$E = -\mathrm{grad}\phi$$

$$\nabla D = \rho$$

j - current density
ρ - charge density
b - charge mobility
E - electric field strength
I - electric current
A - surface of condenser plates
ϕ - electric potential
D - electric displacement

- Potential and electric field in dielectric material

$$\phi(x) = \phi(0) - \frac{\varepsilon b A}{3I}\left[\left(\frac{2I}{\varepsilon b A}x + E^2(0)\right)^{3/2} - E^3(0)\right]$$

$$E(x) = \left(E^2(0) + \frac{2I}{\varepsilon b A}x\right)^{1/2}$$

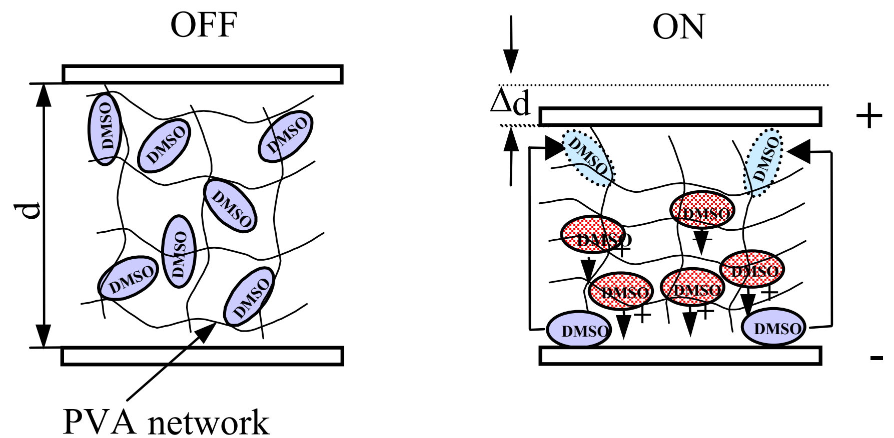
Mechanism of Electric Actuation

- If the dielectric is liquid, Maxwell stress converts to fluid pressure

$$p(x) \approx \frac{9\varepsilon}{8}\left(\frac{V - V'}{d}\right)^2 \frac{x}{d}$$

d - distance between electrodes
$V = \phi(d)$
V' - ionization potential

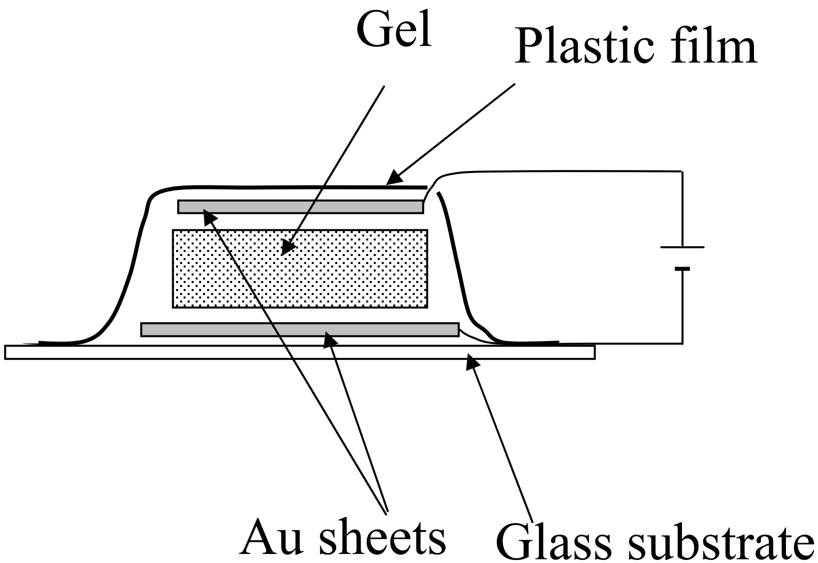
- Charge injection to the solvent (DMSO) in PVA gel, upon applied E-field



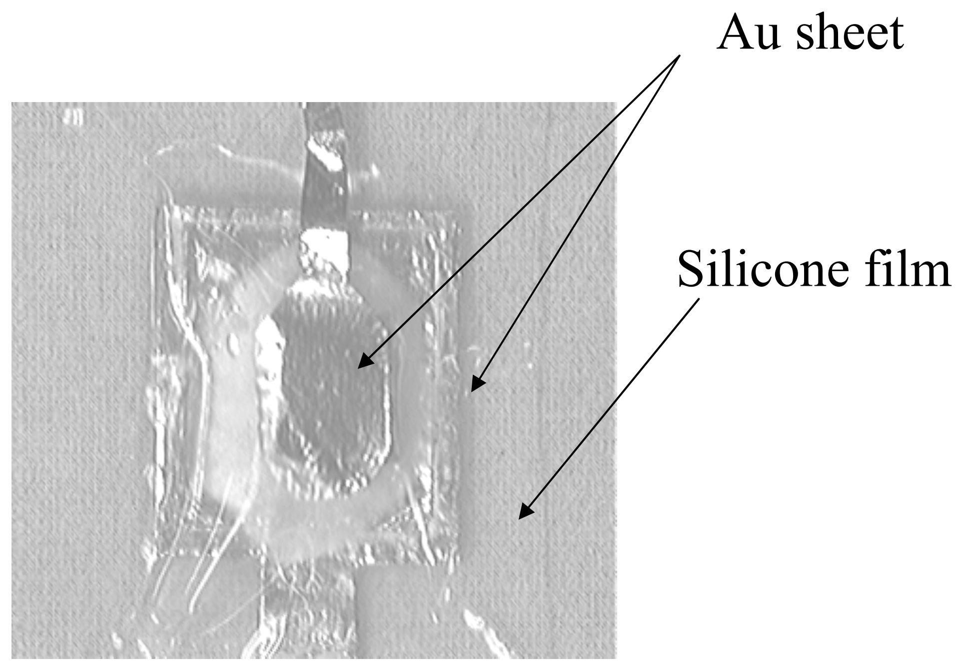
- For the PVA gel having 96-98% liquid phase, solvent pressure is converted to gel stress, with the efficiency η

$$\sigma(x) = \eta \cdot p(x)$$

PVA gel actuator as a switch

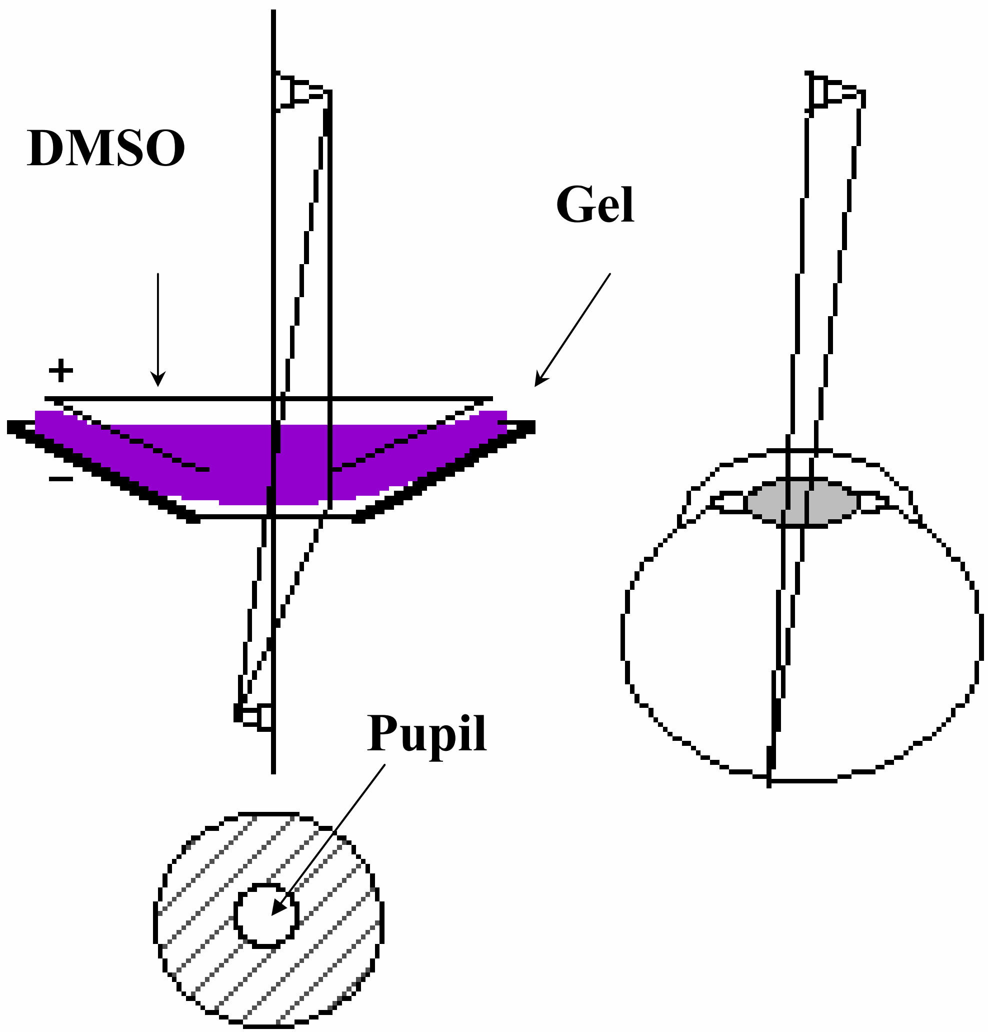


(a) Schematic diagram



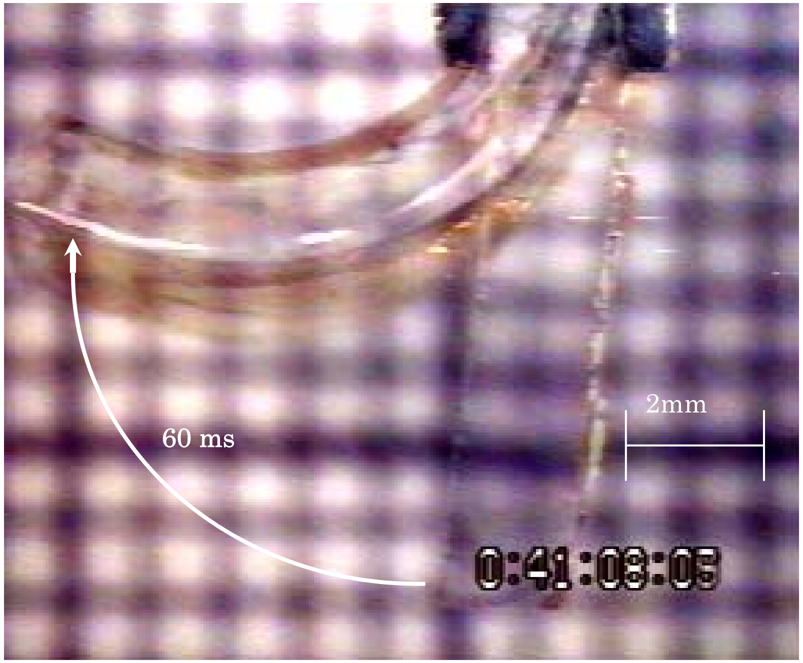
(b) Top view of coated gel

Application potential



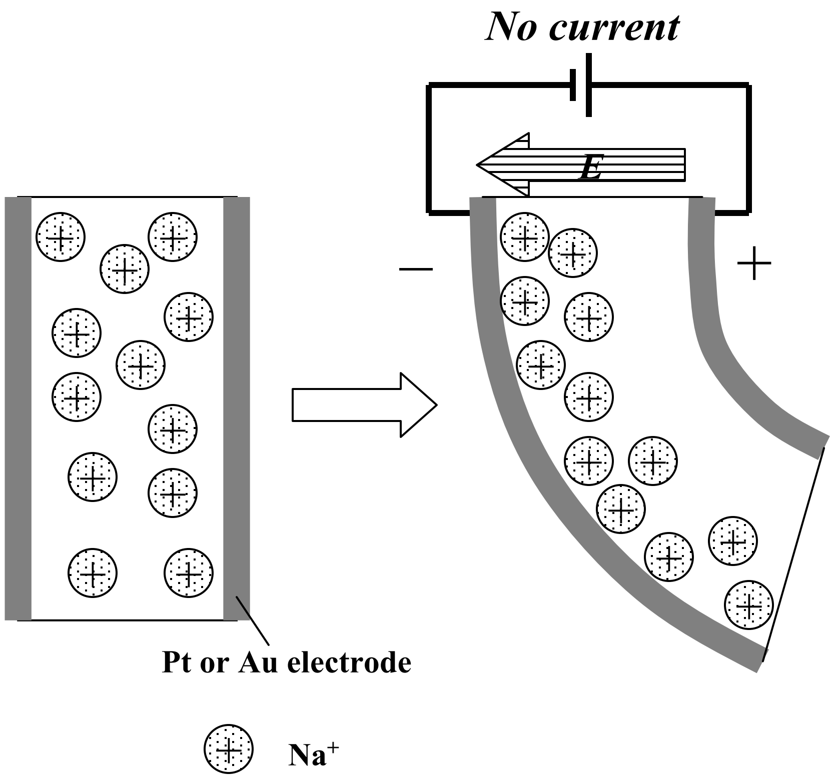
Application potential

Carnivorous Plants



2 types of ion flux through membrane

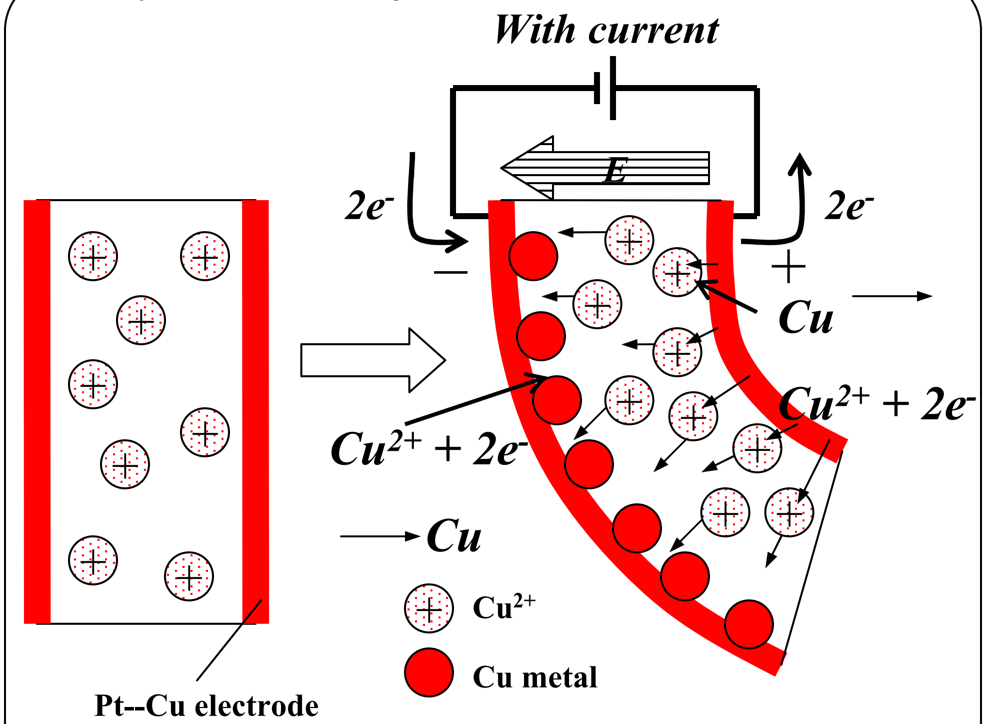
Static ion flux



Redistribution of ions

Electric current is charge current alone

Dynamic ion flux

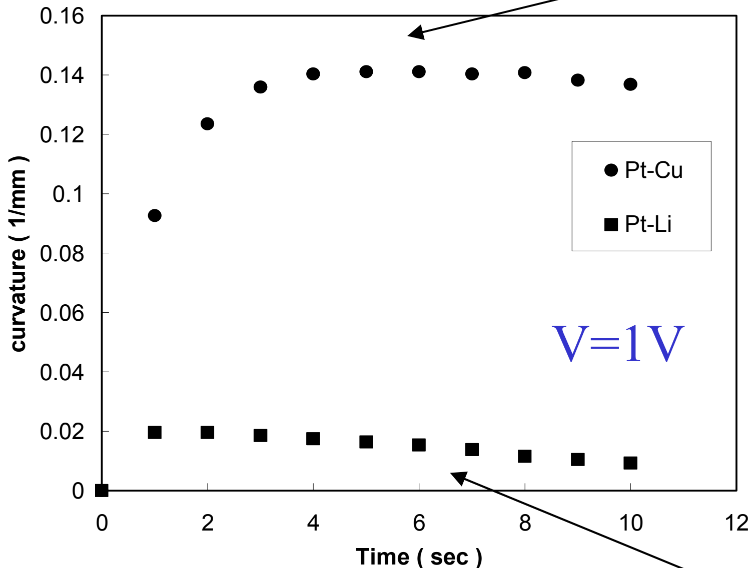


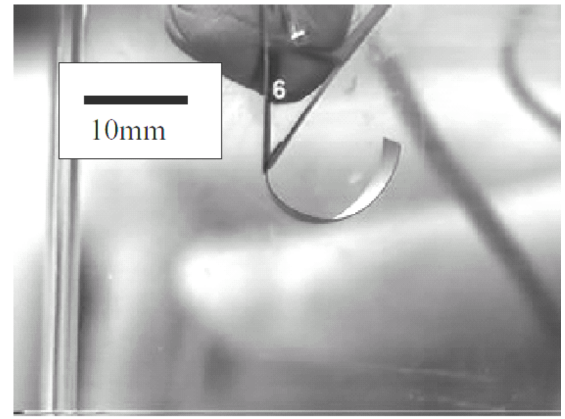
Ion flux with electrode reaction

Electric current continuously flow

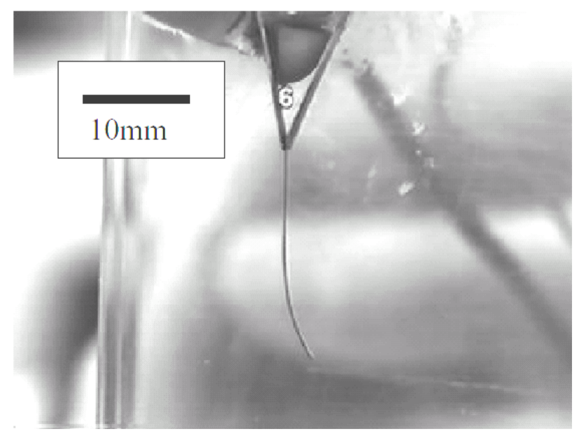
M. Uchida, CIMS

Comparison with Pt electrode





Pt-Cu electrode with copper ion



Pt electrode with Lithium ion

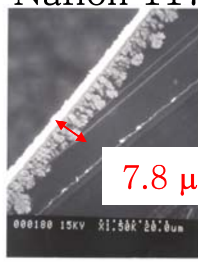
How it works?

Nafion actuator array

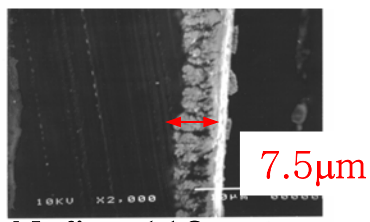
Material design: membranes of different thickness and gold electrodes

After 2 plating cycles

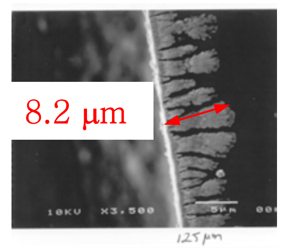
Nafion 117



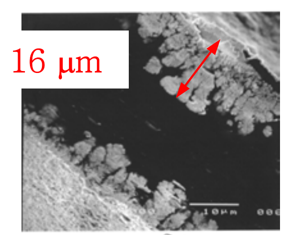
Nafion 115



After 3 and 6 plating cycles

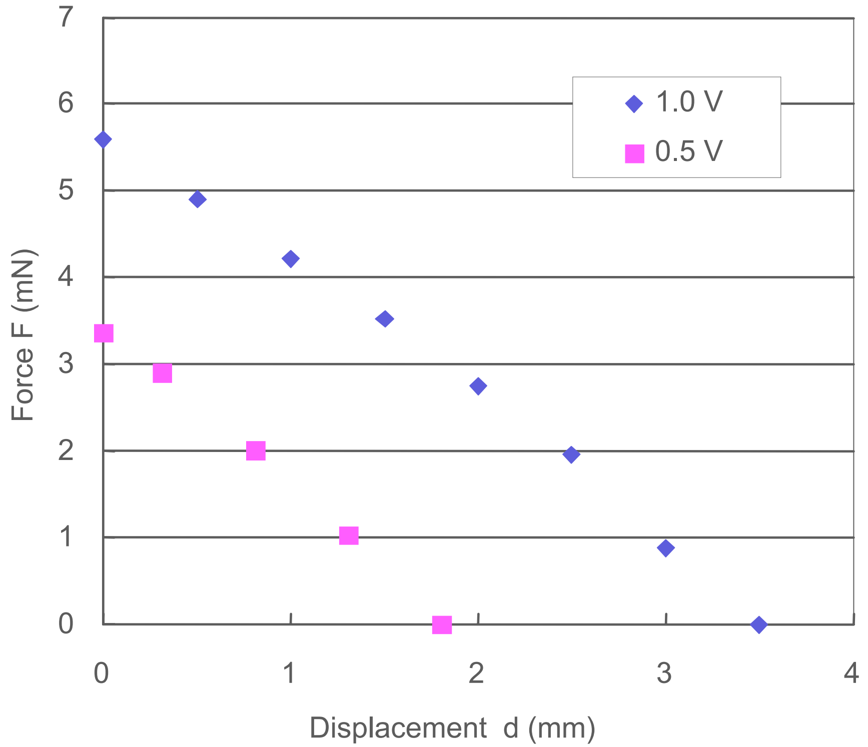


Nafion 112

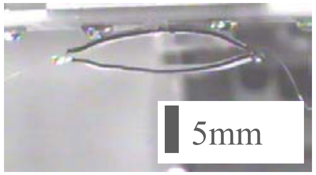


The depth of the fractal structure is mostly controlled by the plating conditions not by the amount of gold.

Nafion loop actuator and performance data



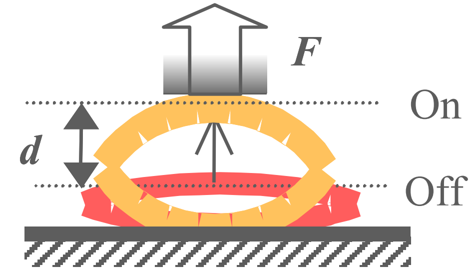
(a)



Off

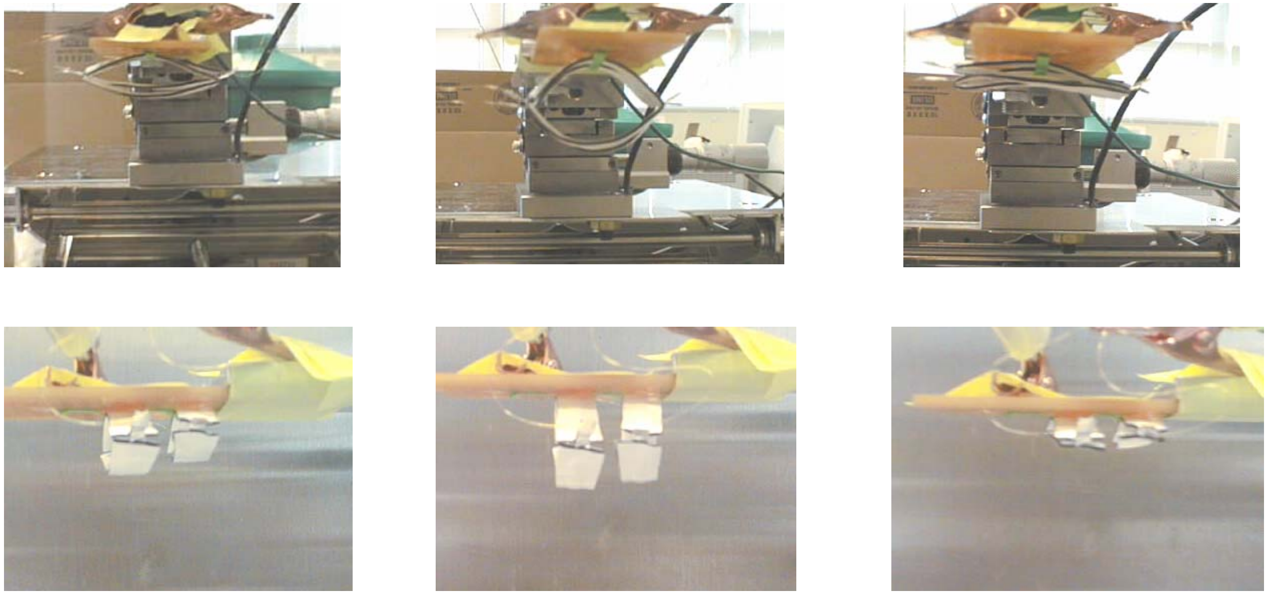
On

(b)

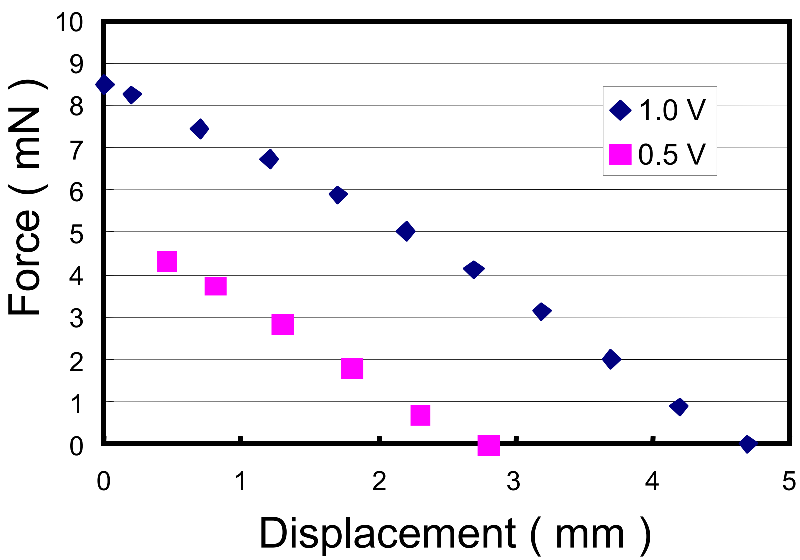


(c)

Parallel device



OFF　　Positive (expand)　　Negative (Shrink)



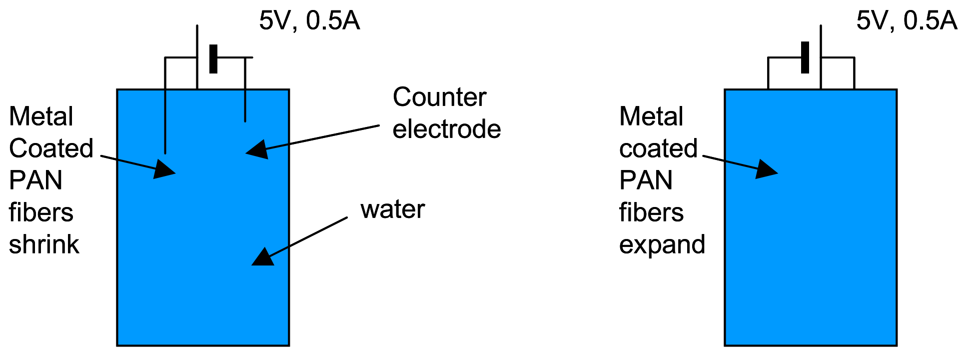
Summary

- Actuation materials

Material	Advantages	Drawbacks
AAm	Large swelling ratio	Low stiffness Slow response
PAN	Faster response Higher stiffness	Limited voltage range
⇨ PVA	Fast response Large deformation Large voltage range	Low stiffness
➡ Nafion	Fast response High stiffness	

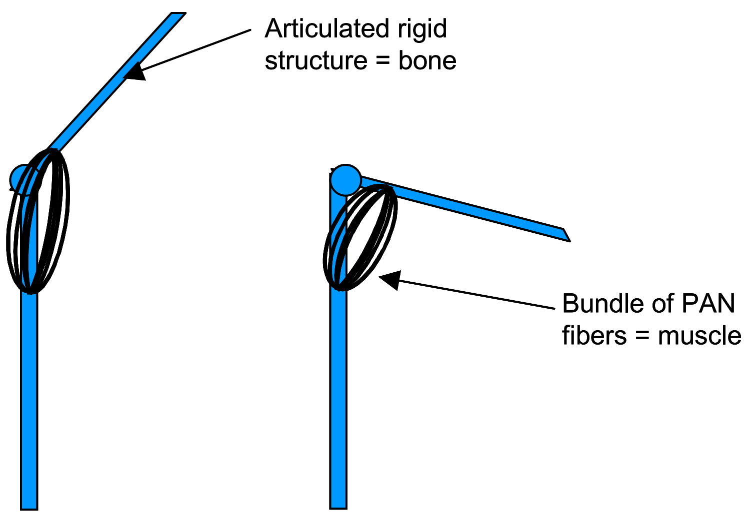
AAm - acrylamide based
PAN - polyacrylnitrile
PVA - polyvinylalcohol

Smart system option with PAN fibers concept

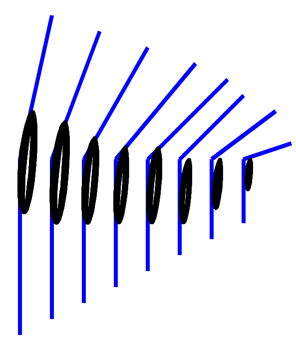


positive electrode: H^+ is created
>acid condition, PAN fibers contract

negative electrode: OH^- is created
>basic condition, PAN fibers expand

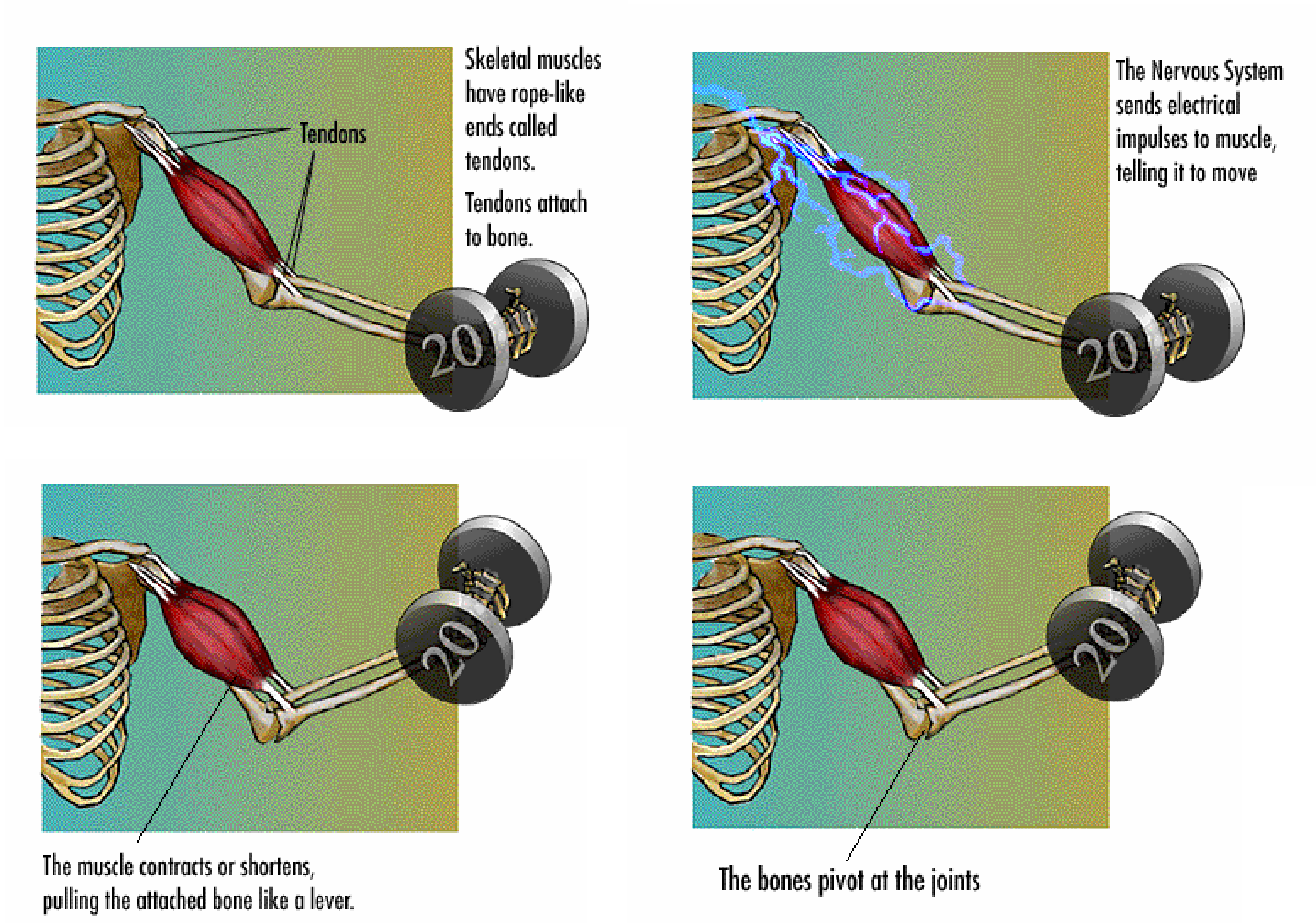


<u>Example of possible fin design</u>



<u>Assembly</u> of articulated bones and contractile actuators creates a conformable fin.
Many shapes are achievable.

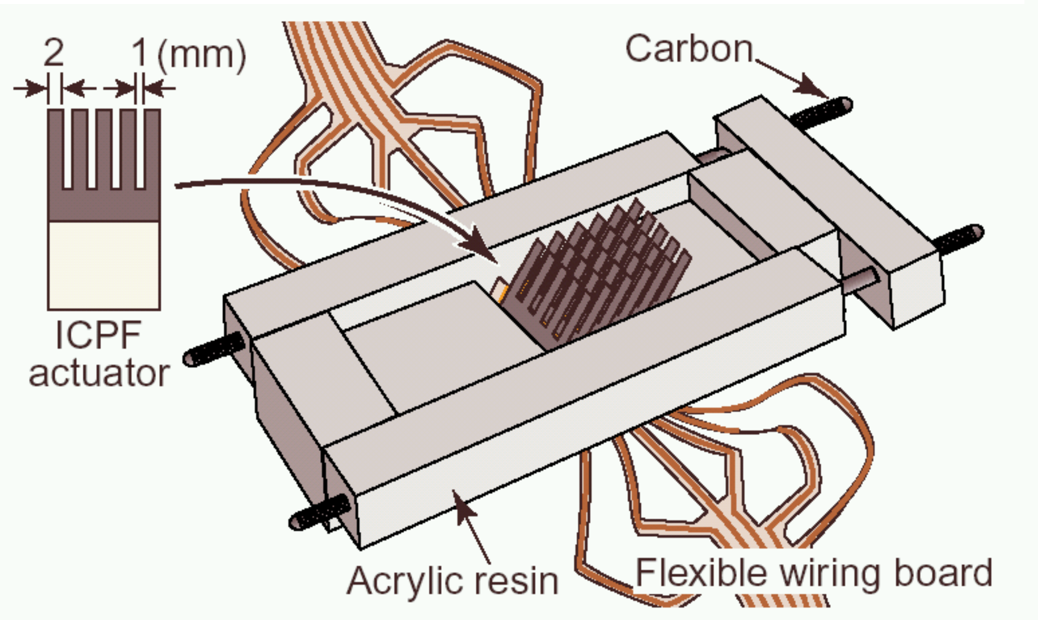
Smart system option with PAN fibers concept: mimic nature!



from www.kidshealth.org/misc_pages/bodyworks/bodyworks.html

Applications potential

Artificial tactile feel display



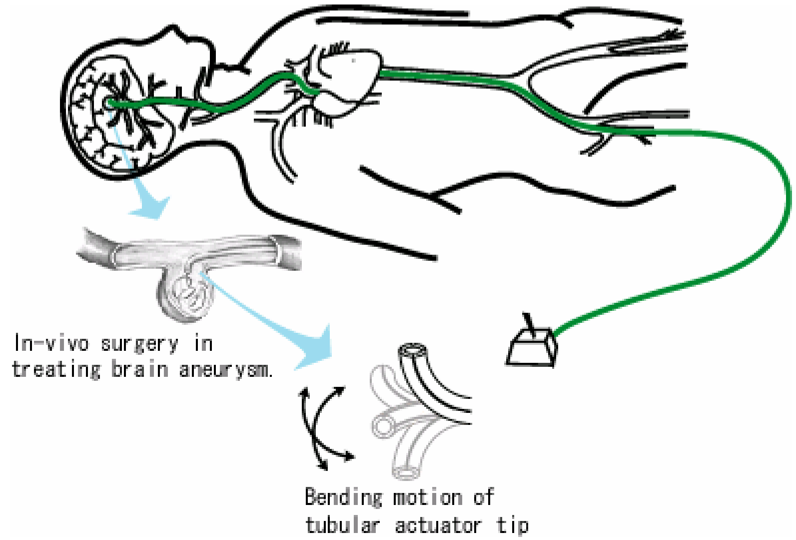
Tadokoro et al.

Kobe University, Japan

Applications

Characteristics of IPMC

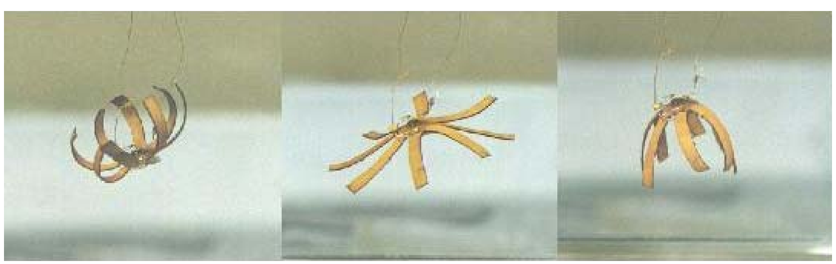
- Low voltage ~1V
- Bending mode of actuation
- Large displacement
- Soft
- Wet
- Ionic nature
- Small scale



www.eamex.co.jp/index_e.html

Applications

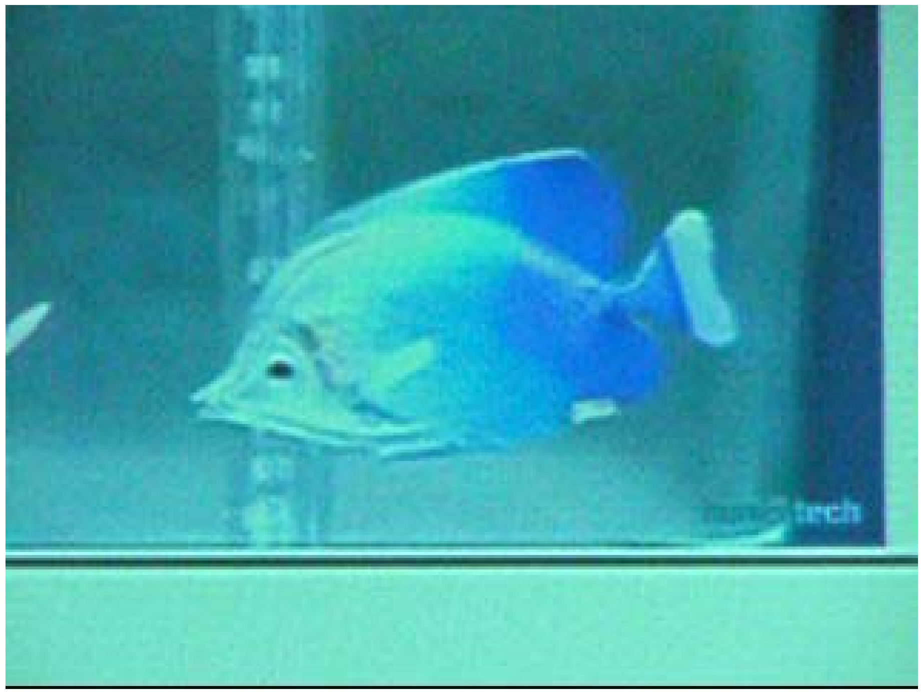
- Micropump
- Catheter
- Robotfish actuator
- Gripper



www.eamex.co.jp/index_e.html

www.eamex.co.jp/index_e.html

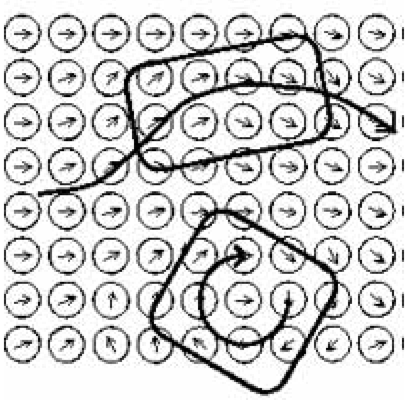
Fleminon Fish



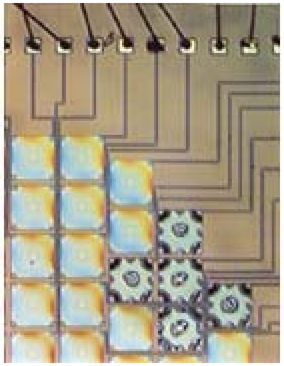
www.eamex.co.jp/index_e.html

Applications

Actuator arrays



http://voronoi.sbp.ri.cmu.edu/projects/prj_virtualvehicle.html



http://bifano.bu.edu/tgbifano/Web/%B5Valve.html

www.sciam.com

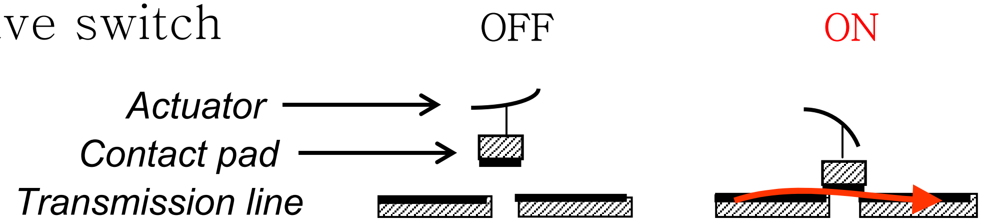
Electroactive polymer actuator arrays
Low cost, low power consumption, large displacement, softness
Polymer nature, compatible with wet environment

How it works?

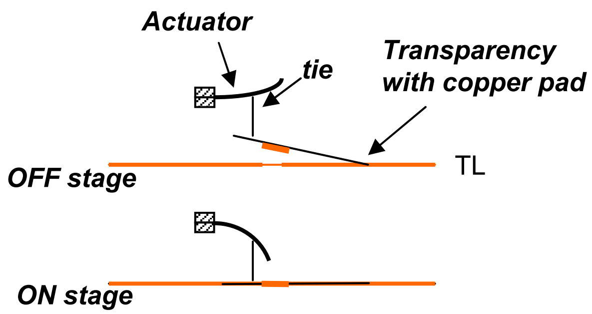
Flemion actuator array

Actuator design: Flemion beam actuator for microwave switch

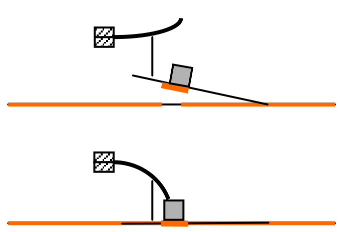
Microwave switch



Switch design: actuator above board and lifting contact pad in OFF stage. Contact pad resting against the TL in ON stage

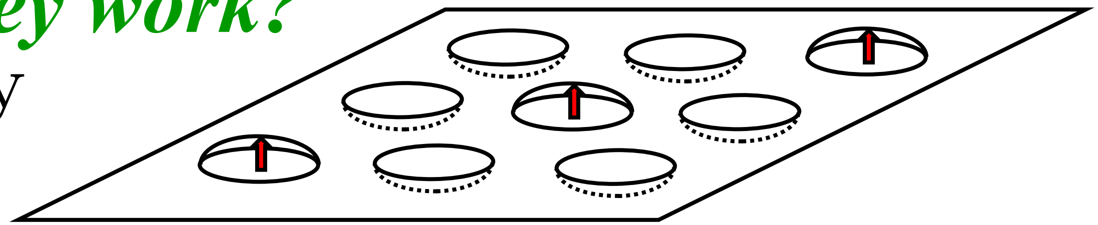


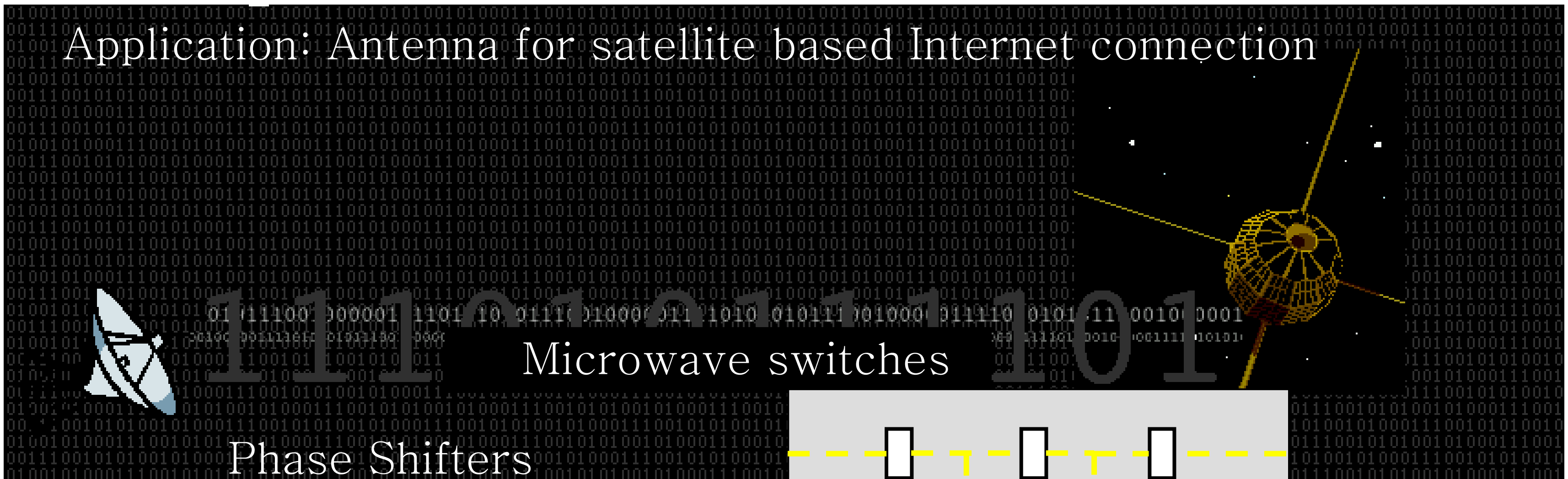
With additional weight



How they work?

Actuator Array

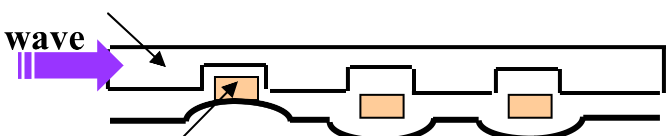


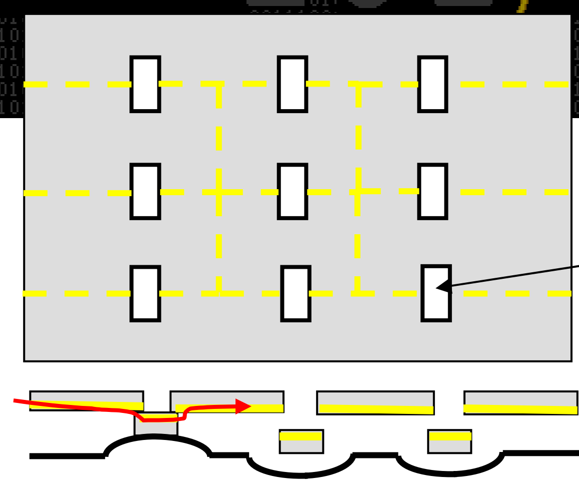


Application: Antenna for satellite based Internet connection

Microwave switches

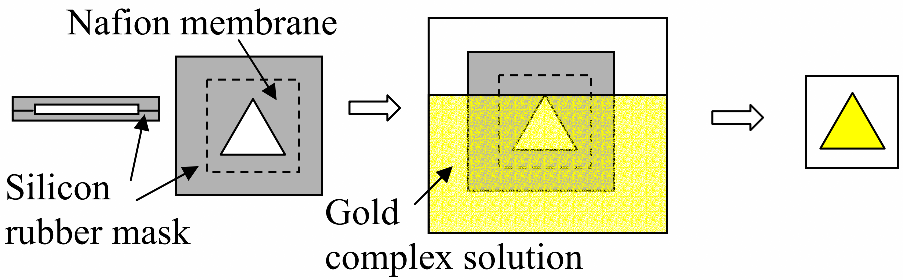
Phase Shifters

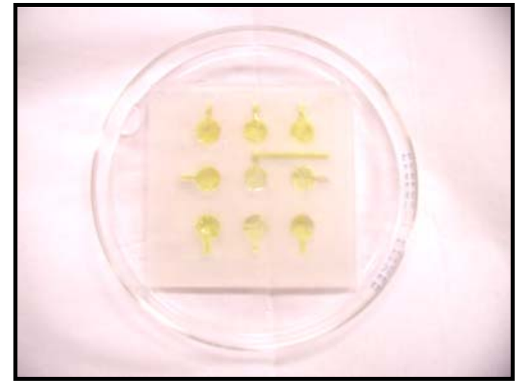




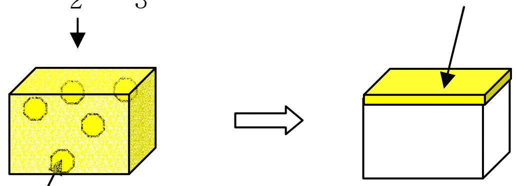
3x3 Array from Nafion 112 with gold electrodes and TEA ion: Patterning

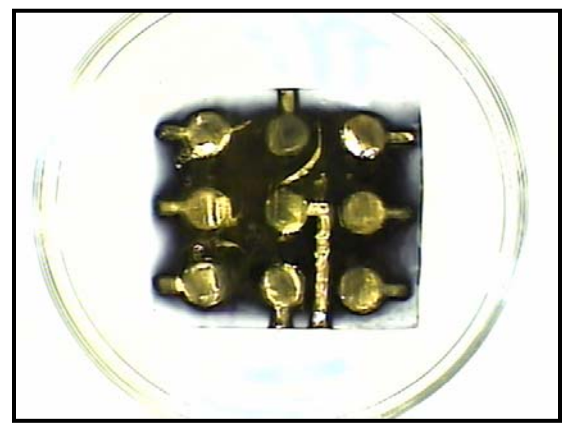
We use hydrophobic masks to selectively swell the membrane with the gold complex



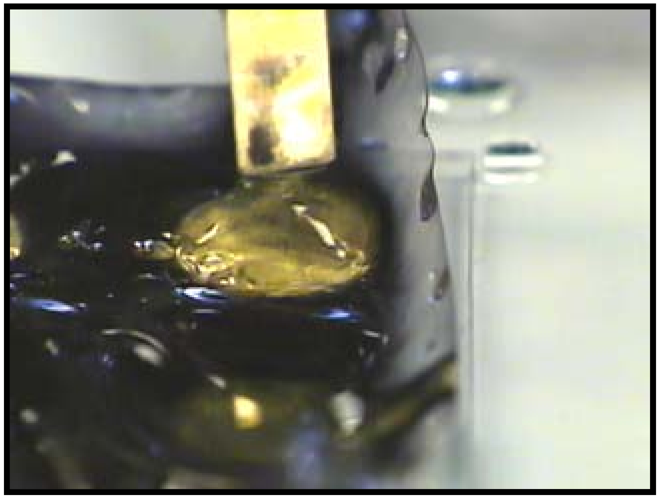


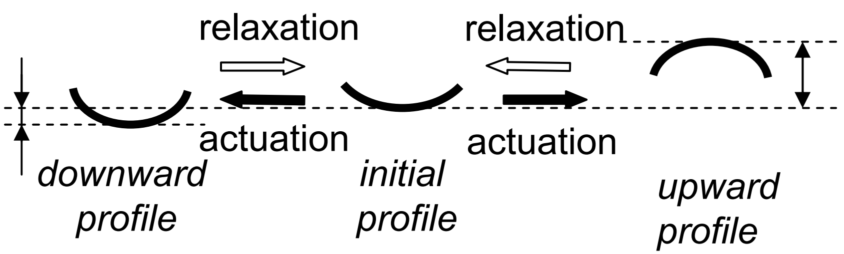
Gold is plated by reduction of the gold complex

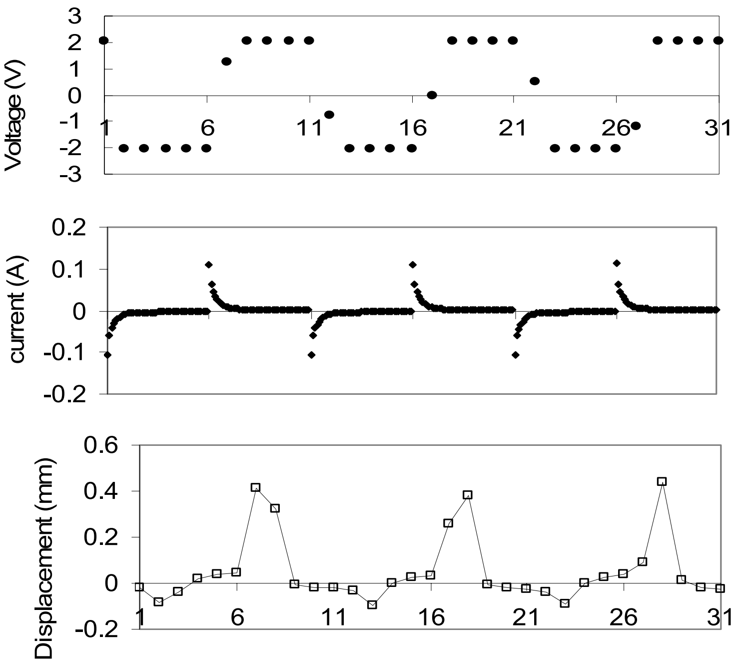




How it works?







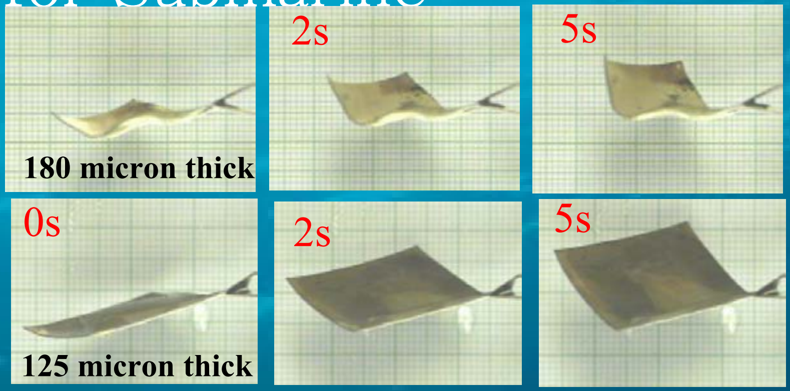
Voltage, current and displacement versus time of the active cell

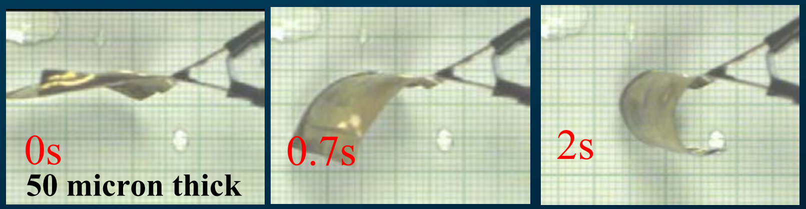
How they work?

At time = 0sec
Voltage goes

Application: Conformable fin for Submarine

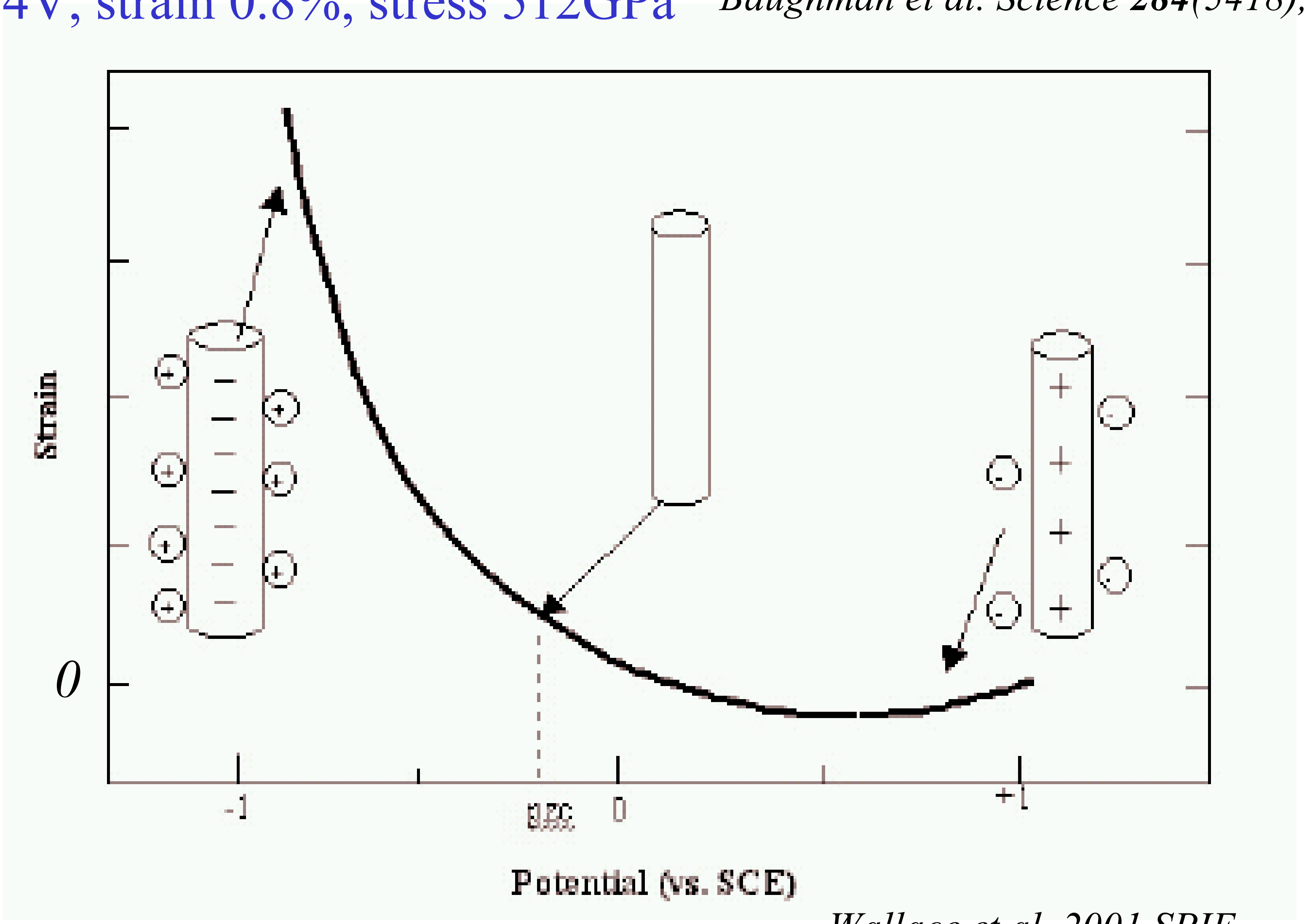
Nafion is an Ion Exchange Polymer Membrane. Negative charges are attached to the polymer backbone. Next to each negative charge is a positive Counter ion and some water molecules. If we apply an electric field across Nafion the positive ions move and the whole membrane starts moving.
This works best if the membrane is fully hydrated. Therefore Nafion actuators work best in water





Carbon nanotube actuator

4V, strain 0.8%, stress 512GPa *Baughman et al. Science **284**(5418),1999*

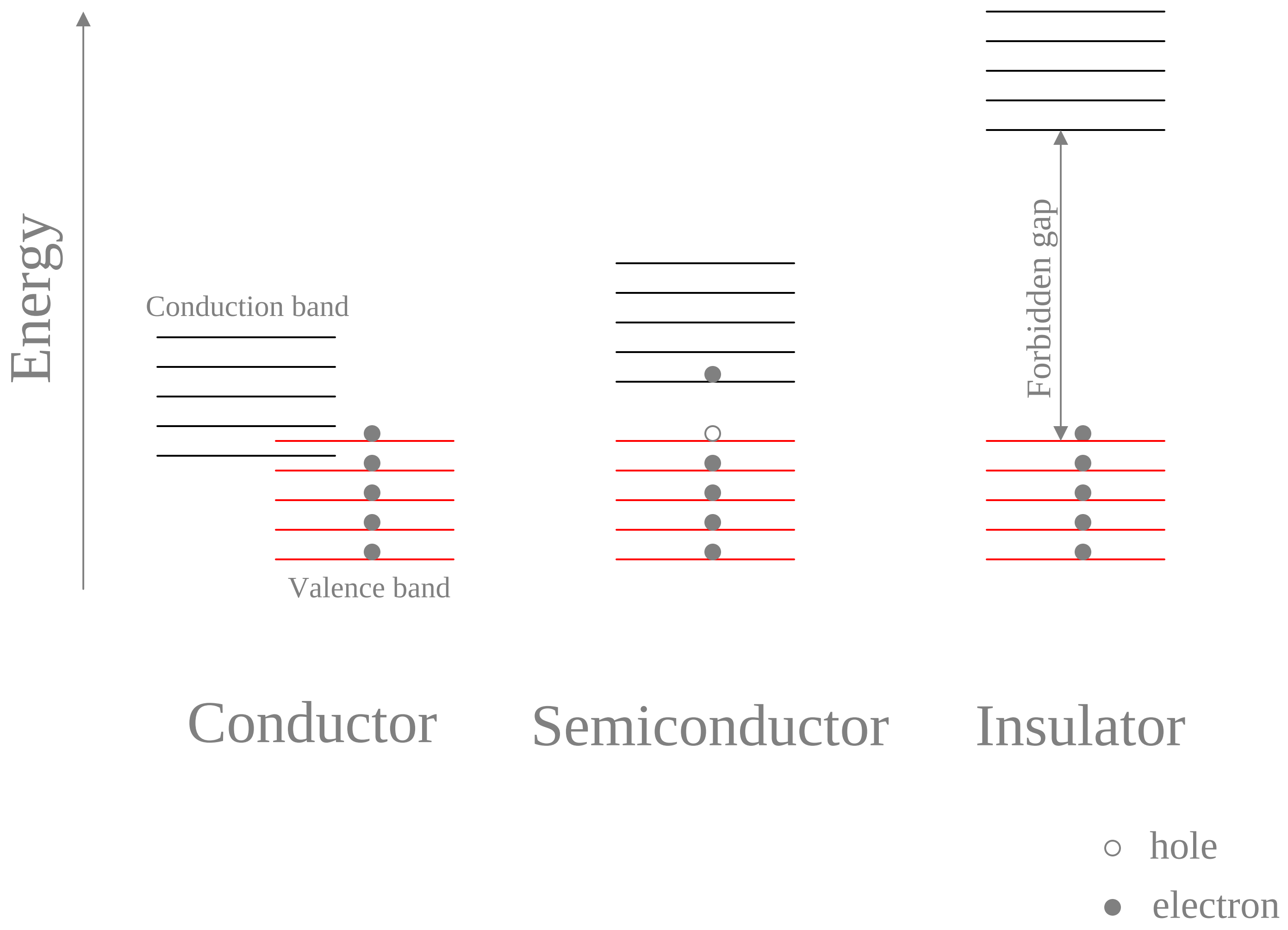


Wallace et al, 2001,SPIE

Conducting Polymers

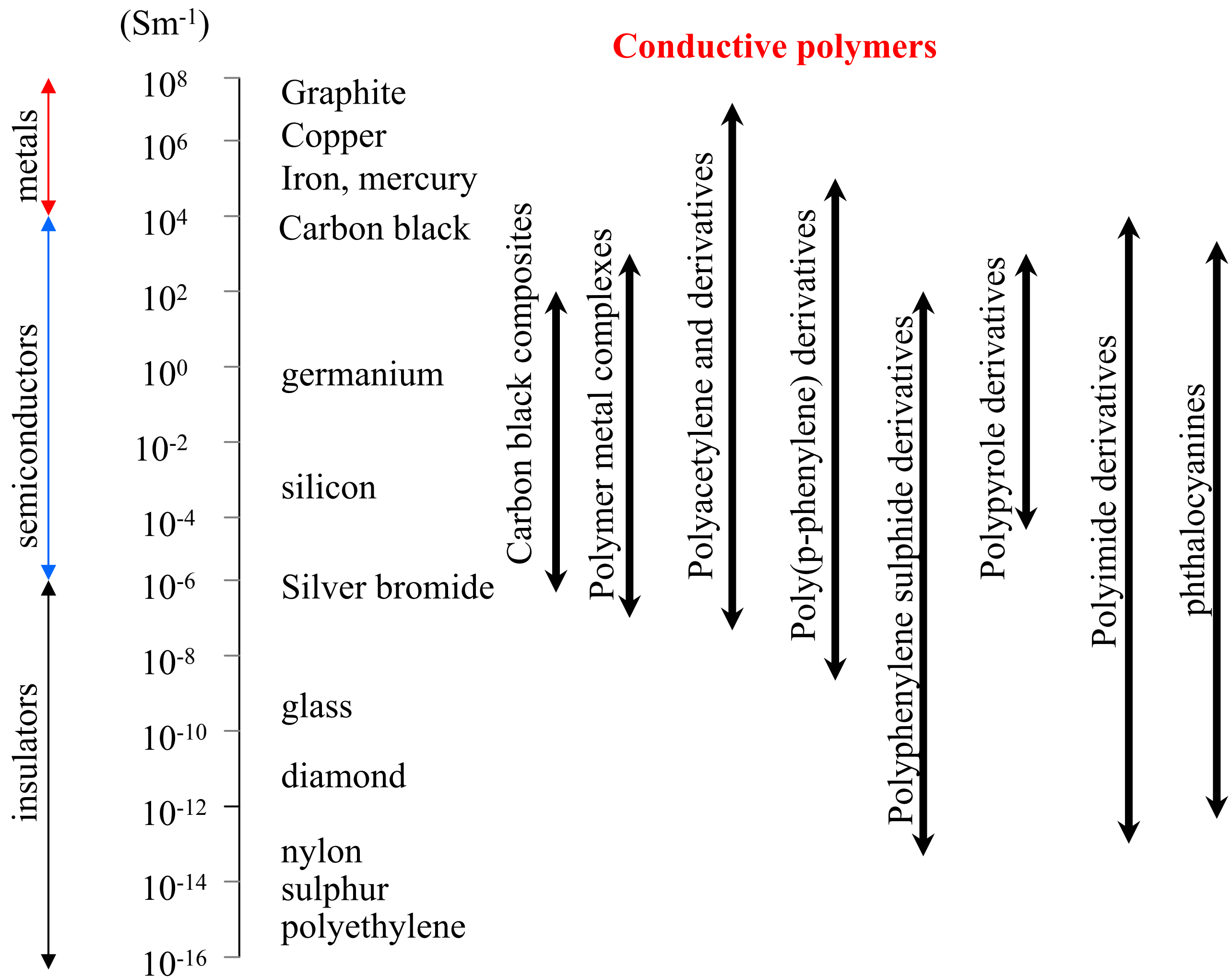
- Insulating polymers:
  familiar uses include cable sheathings, dielectric layers and films as in capacitors, printed circuit substrates.

Conduction mechanisms



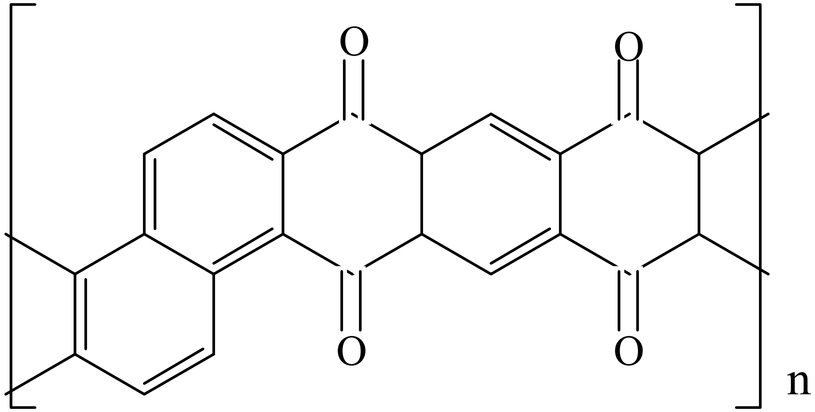
w.wang

Representation of energy band for metal semiconductor and insulator

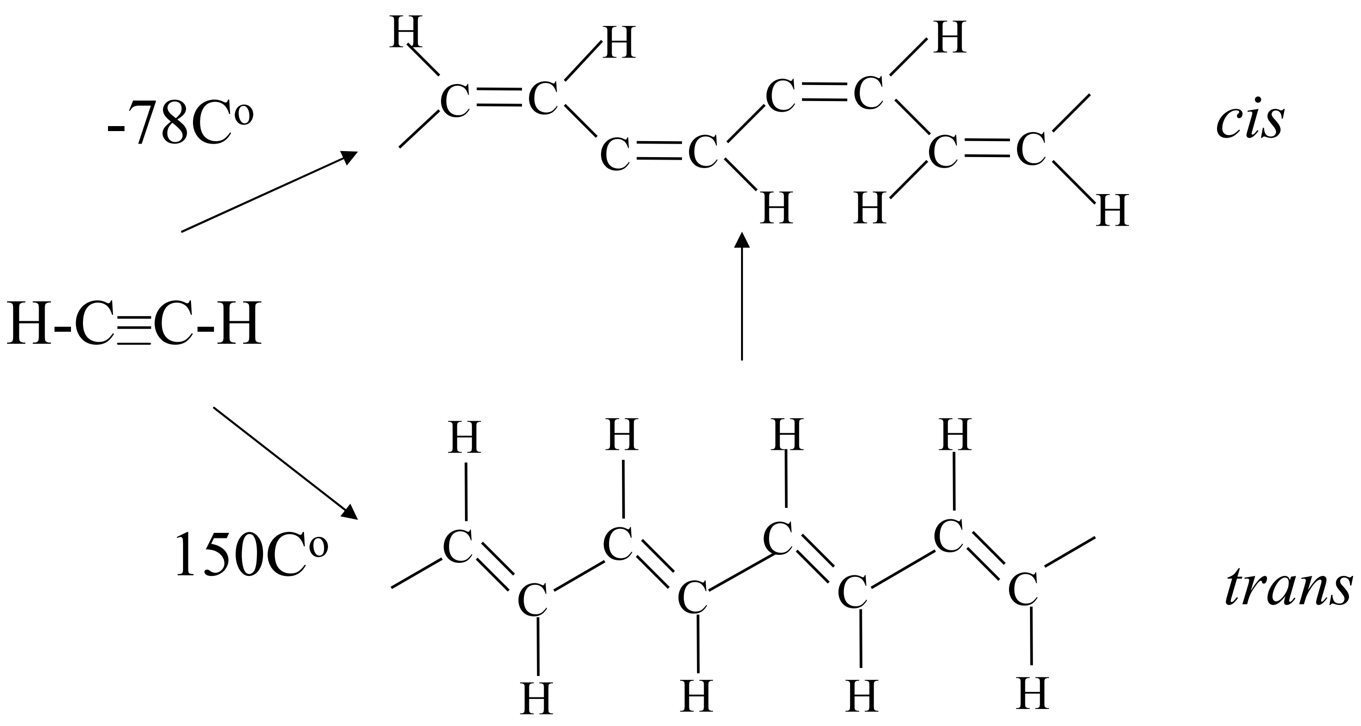


Conductivities of various elements, compounds and polymers

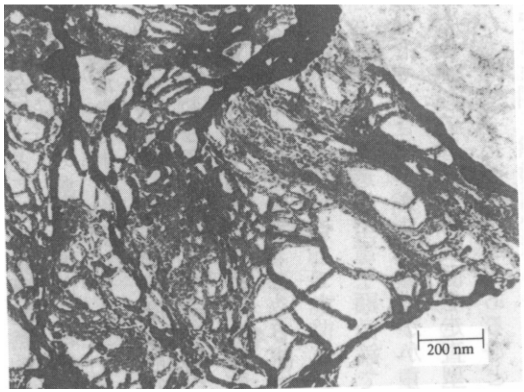
PolyPyrolysis



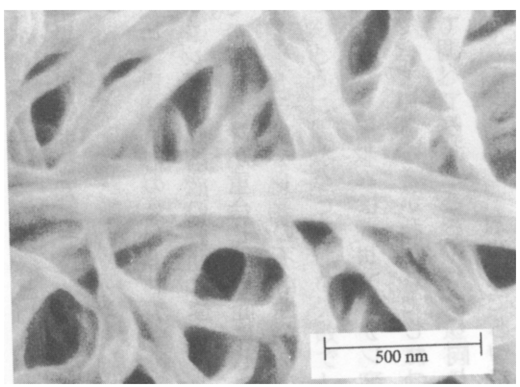
Polyacetylene



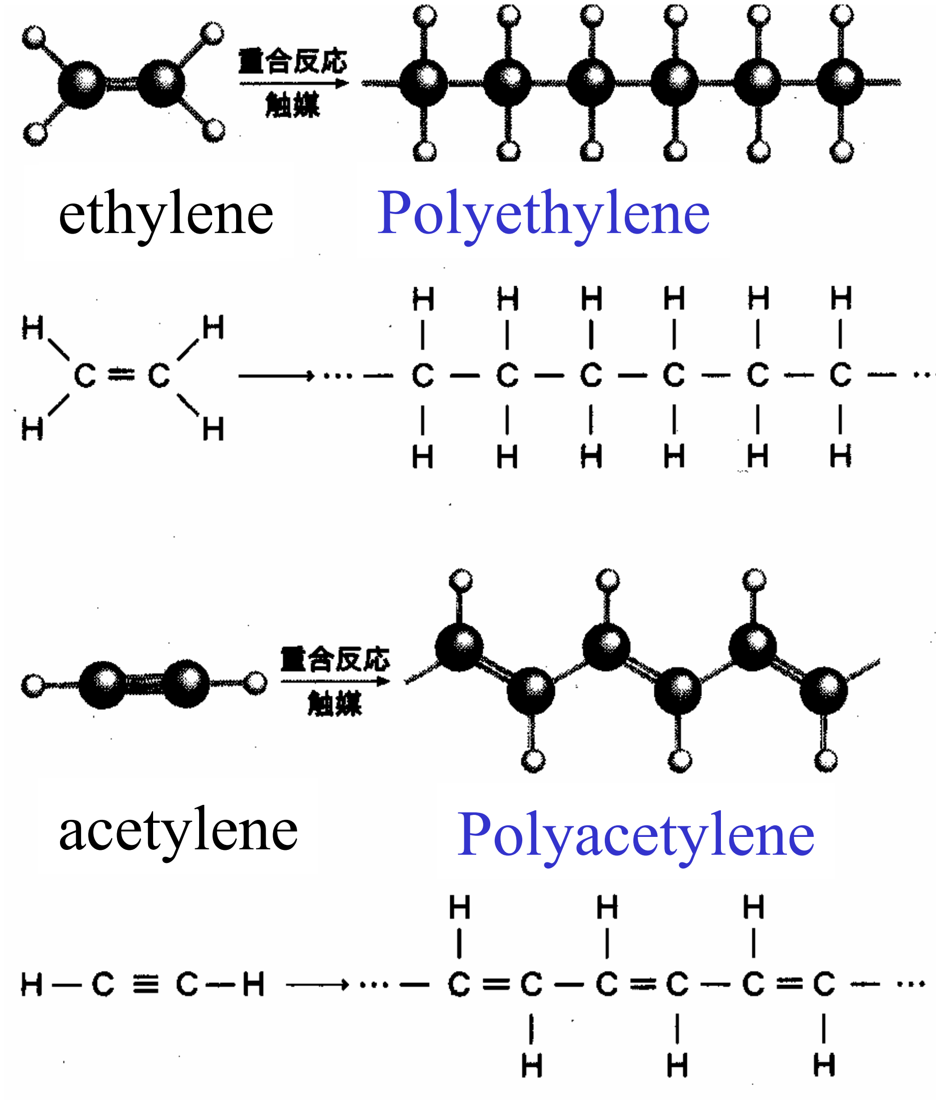
Difference structure between polyethylene and polyacetylene



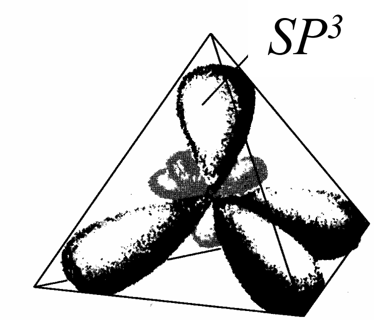
(a) Polyactylene thin film

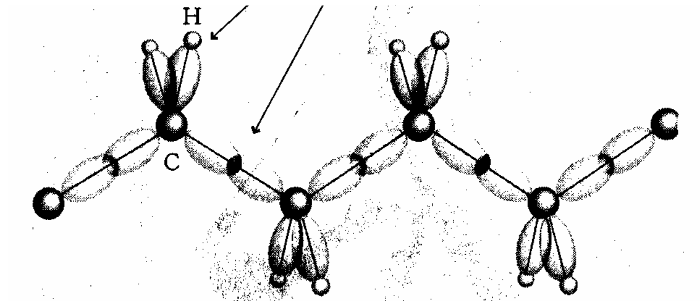


(b) Polyactylene thick film

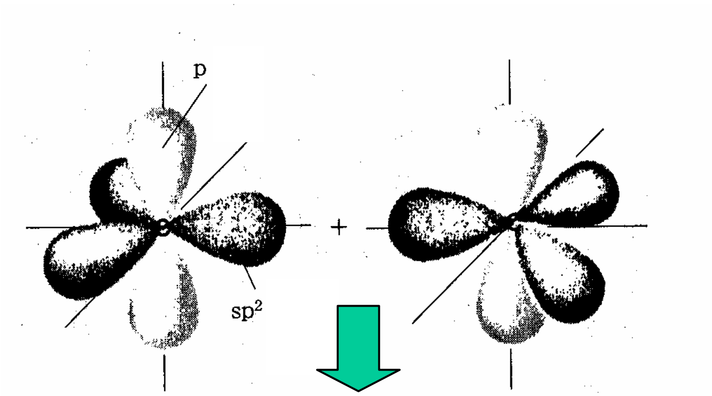


How they work?





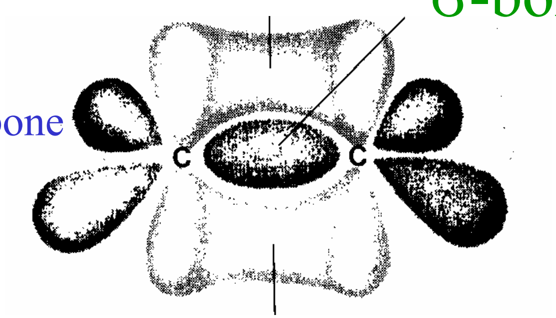
Polyethylene



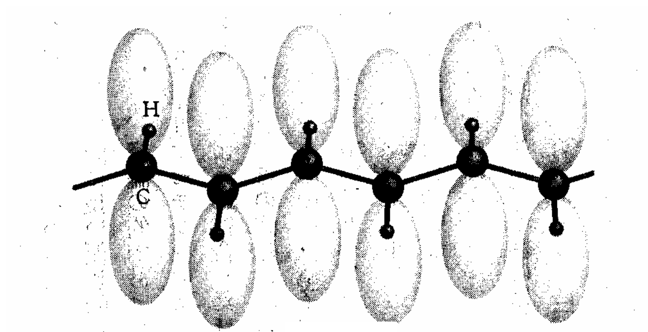
π-bond

σ-bond

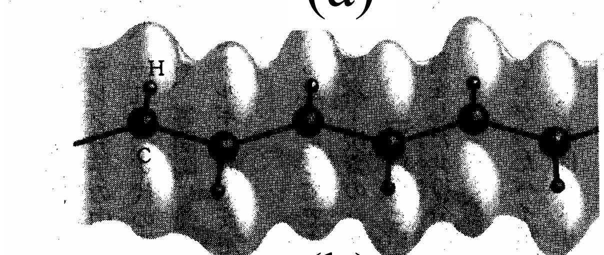
C-C double bone



π-bond



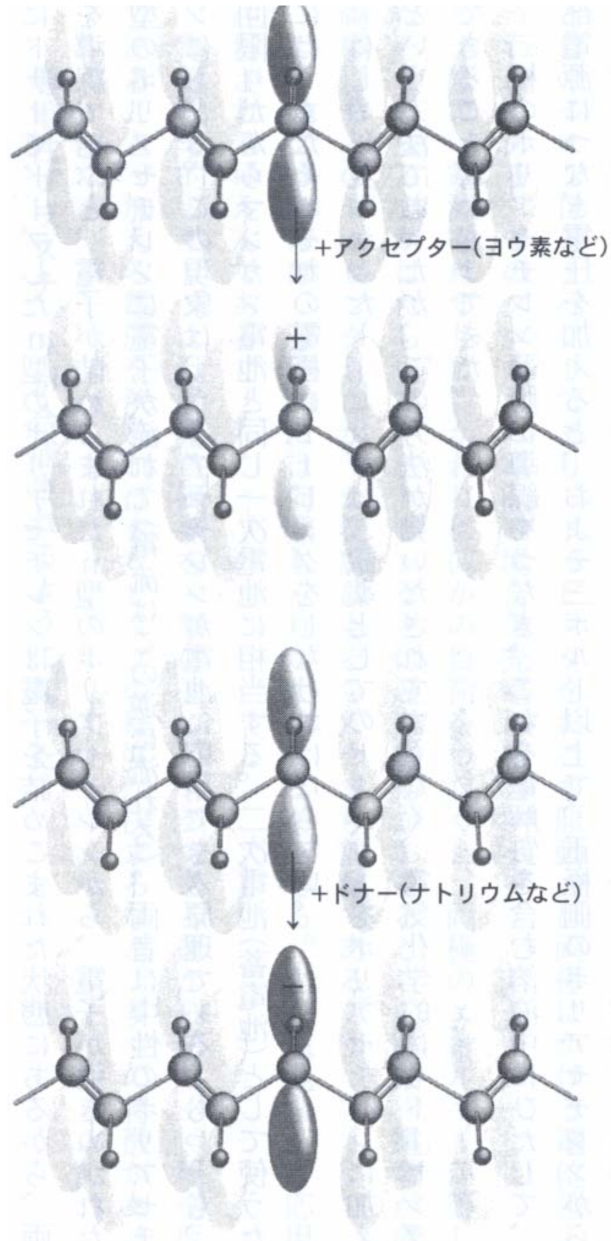
(a)



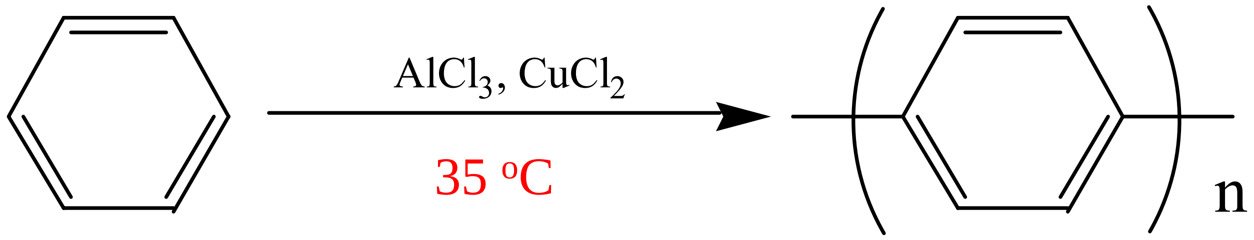
(b)

Polyactylene

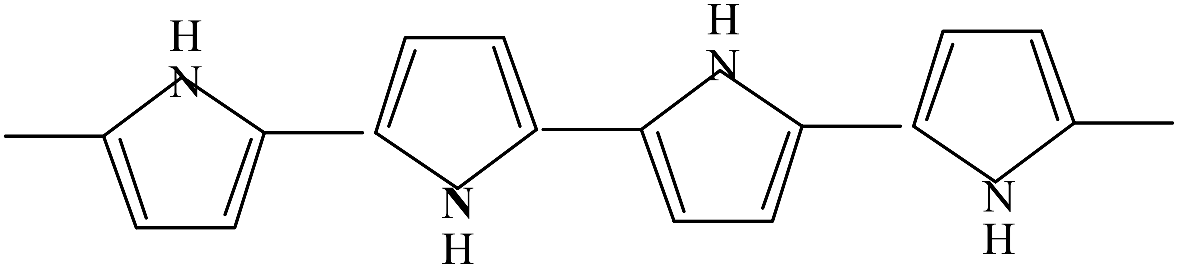
Polyacetylene after doping



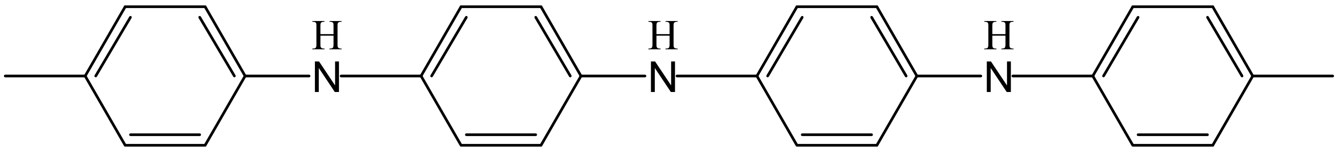
Polyparaphenylenes



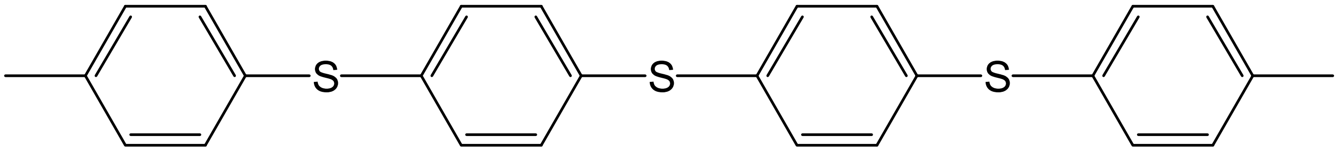
Polypyrrole



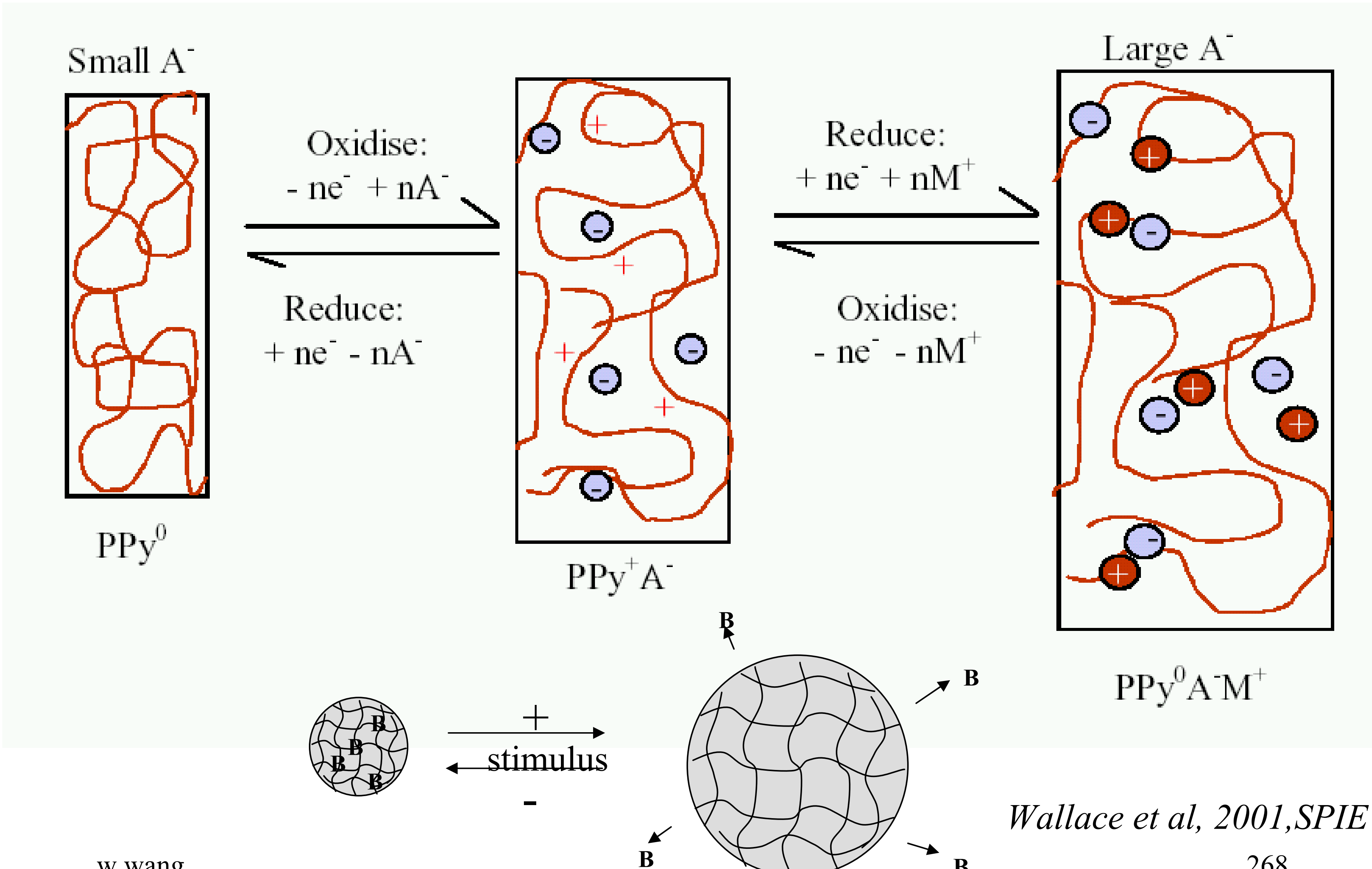
Polyaniline



Polyphenylene sulfide



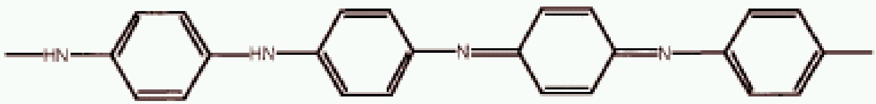
Active drug delivery system and actuator

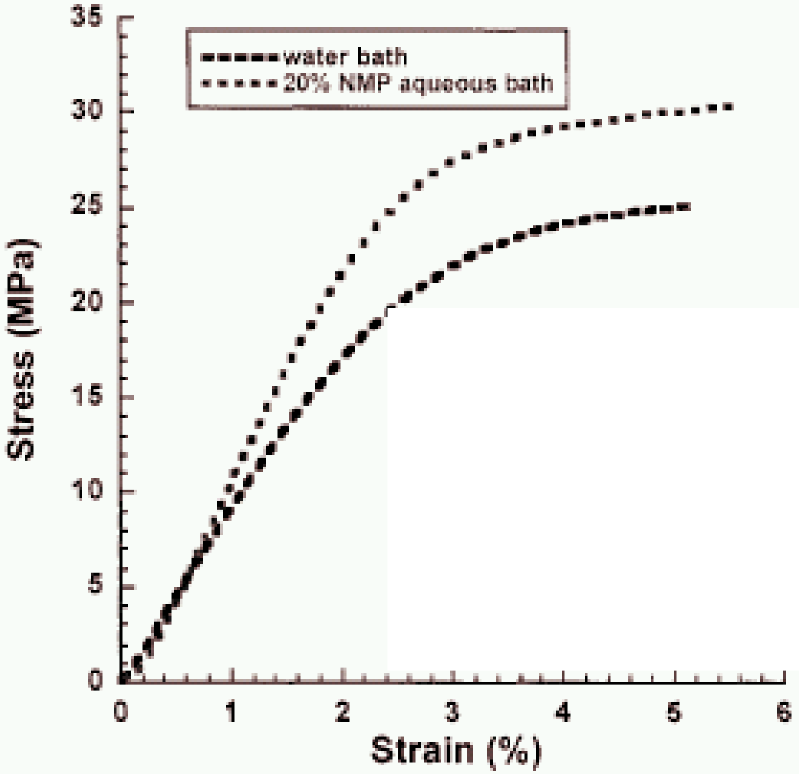


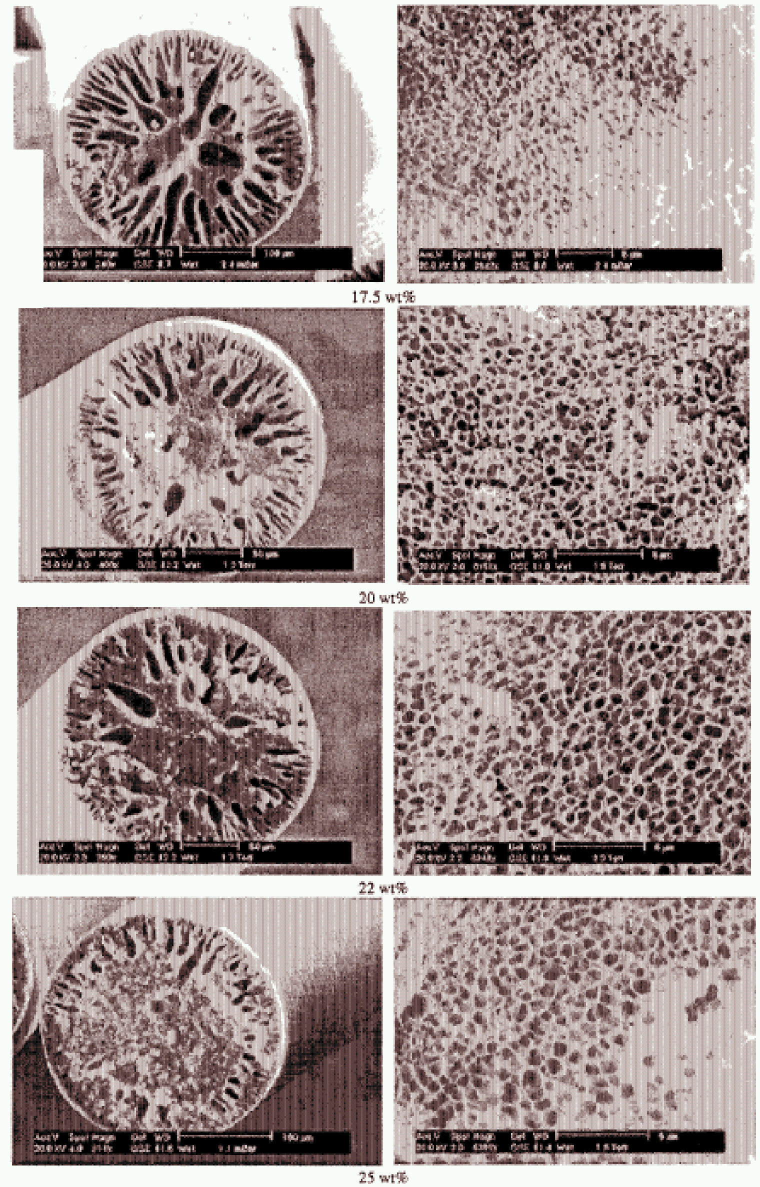
Wallace et al, 2001,SPIE

Sensing fiber

Wet-spun polyaniline (PANI) fiber







Cross-section micro-structure

Yang et al. 2001

Clothing technology

Applications of EC Polymer

Present Commercial Products:

- **Plastic rechargeable batteries**
  Polyactylenes (PA) and polyanilines (PAn)
  cell phone, back-up power source for personal computer, solar-powered calculator etc

- **Sensors**
  Polypyrrole (PPy), PA, Polythiophone, Polyparaphenylenes (PPP) and PAn
  Sensing vapours of nitromathane, toluene, benzene, methanol and water
  Determining the concentration of ions in solution
  Electrochemical biosensors

- **Shielding**
  PAn etc
  Electrostatic discharge and electromagnetic interference/ratio-frequency interference applications

Applications of Conductive Polymer

- Printed circuit boards

  Flexible insulating substrate with a conducting pattern that could form the basis of printed circuit board

  Complex multilayer board

- Condenser

- Various semiconductor devices

- Electrochromic displays, smart window

- Solid electrolyte (doped polypyrrole) and etc

Applications of EC Polymer

Present research

- Diode

- Display for mini television

Future

- Electronics

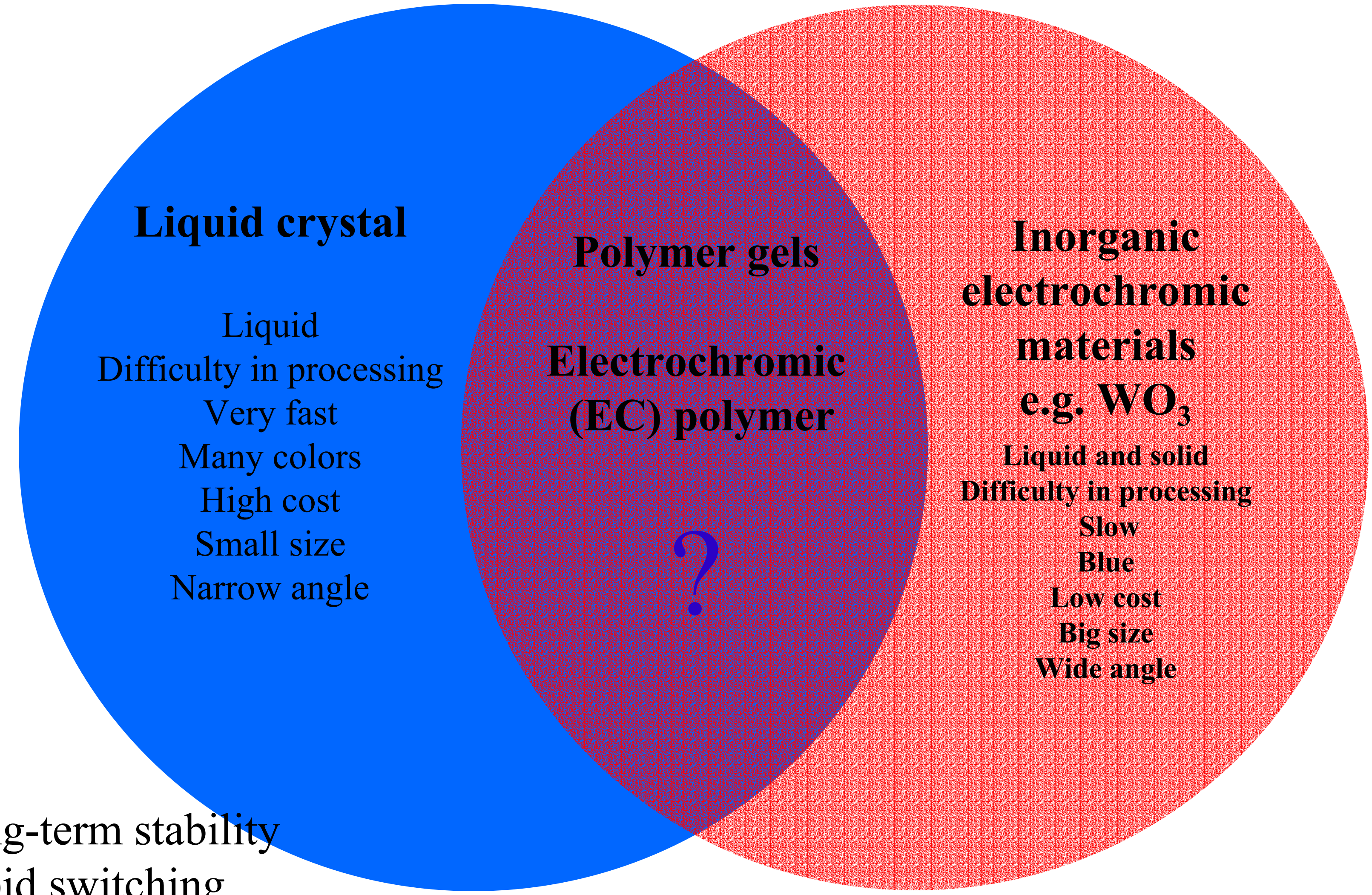
Molecular diode, molecular computer and electroluminescence and etc.

Design of smart window technology

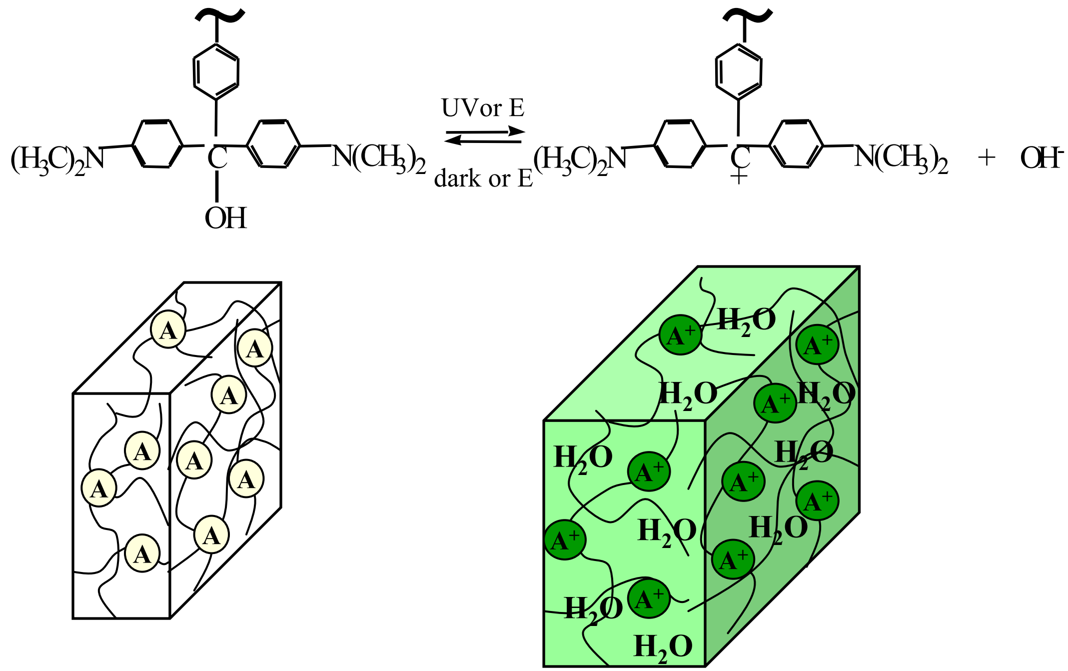
Outline

1. Background
2. Color changeable gel
3. New design of electrochromic color changeable device
4. Mechanism for color change
5. Preparing three parts for the device
6. Assembly
7. Testing and analysis of performance
    - Transmittance
    - Optical switching speed
    - Repeatability (Electrochemistry study)
    - Voltage effect on color change speed
    - Voltage effect on color change degree
    - Temperature dependence
8. Application potentials

Background



long-term stability
rapid switching
large changes in transmittance



Machanism for color and volume change of copoly(Aam/vdMG) gel under UVor pH(Electric current) where A and A^+ represent the neutralized and the ionized vdMG, respectively

Changing concentration of vdMG in the gel to control the degree of color change, color changed under E-current, 1.5A,5V at 20 °C

RESULTS AND DISCUSSION

- **Color change speed**

stimuli	UV	pH	E-current	UV & E-current	E-current & Na_2SO_4	E-current & AAm gel
light green to dark green	3 min	1.5 min	40 s	30 s	23 s	19 s
dark green to light green	15 h	2min	60 s	60 s	23 s	19 s

Previous results, Irie et al. → ← present results

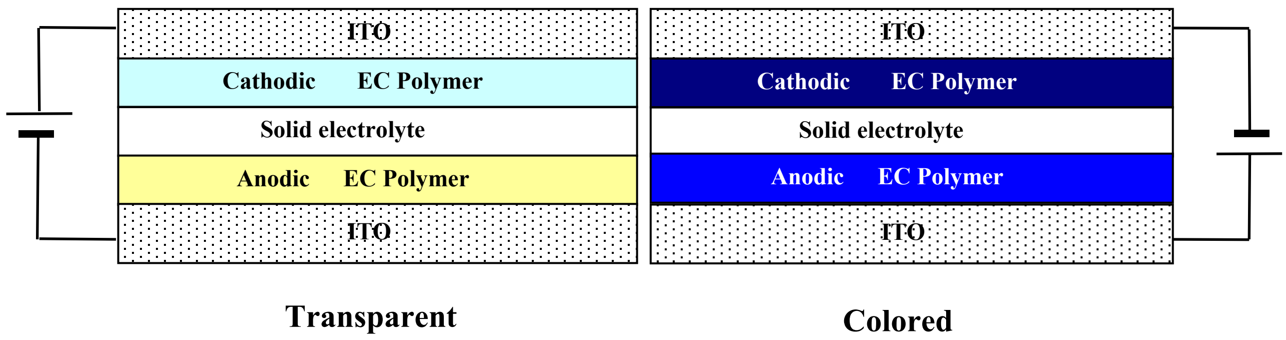
- **Effect of gel thickness on actuation speed under applied E-current**

Employed the most effective setup given in above

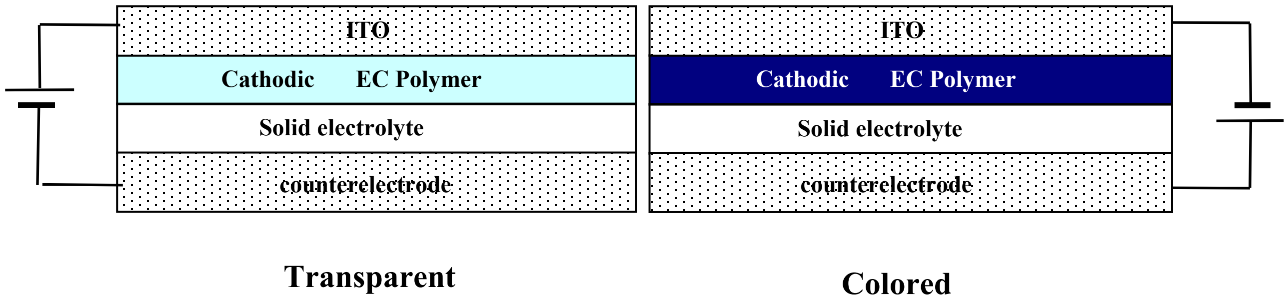
thickness	1.0mm	0.75mm	0.50mm	0.25mm	0.125mm
light green to dark green	25s	19s	15s	11s	9s
dark green to light green	25s	19s	15s	11s	9s

Schematic diagram of device design using color changeable EC polymers

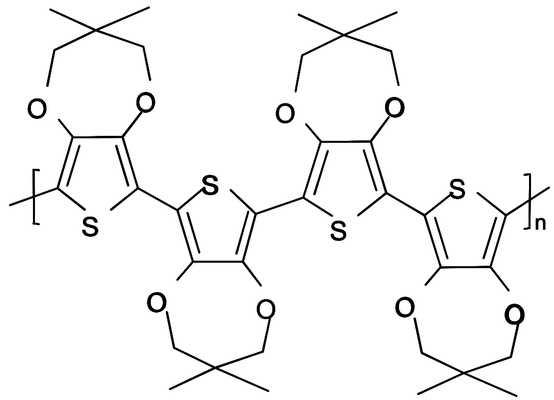
Three-layer scheme:



Two-layer scheme:



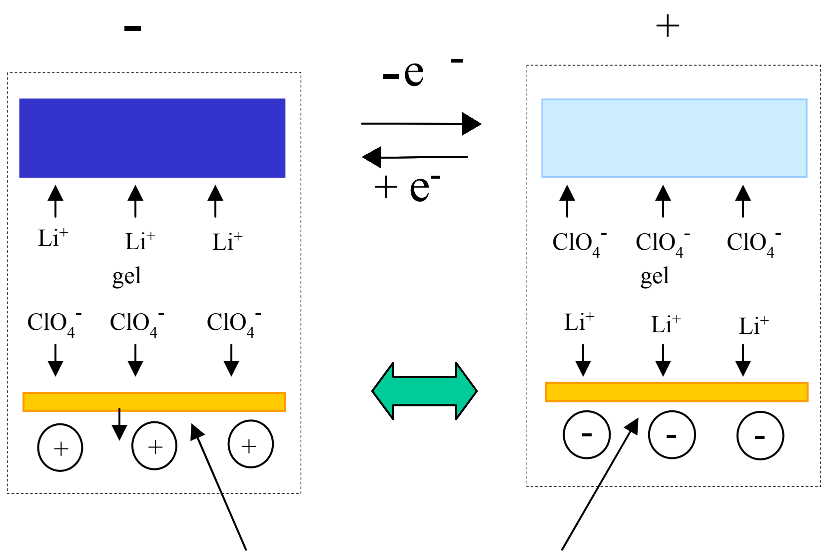
Schematic diagram of mechanism for color change of cathodic EC polymer, PProDOT-Me_2



Cathodic EC polymer

Dark blue

Neutral state



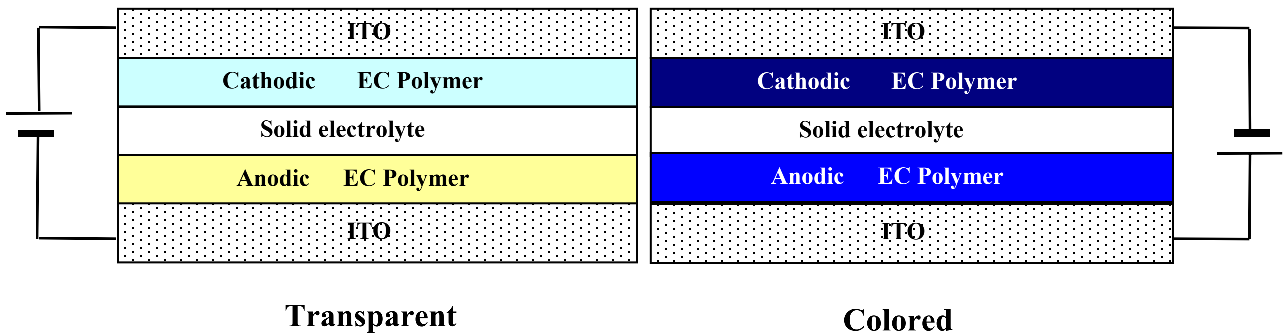
Transparent

p-Doped state

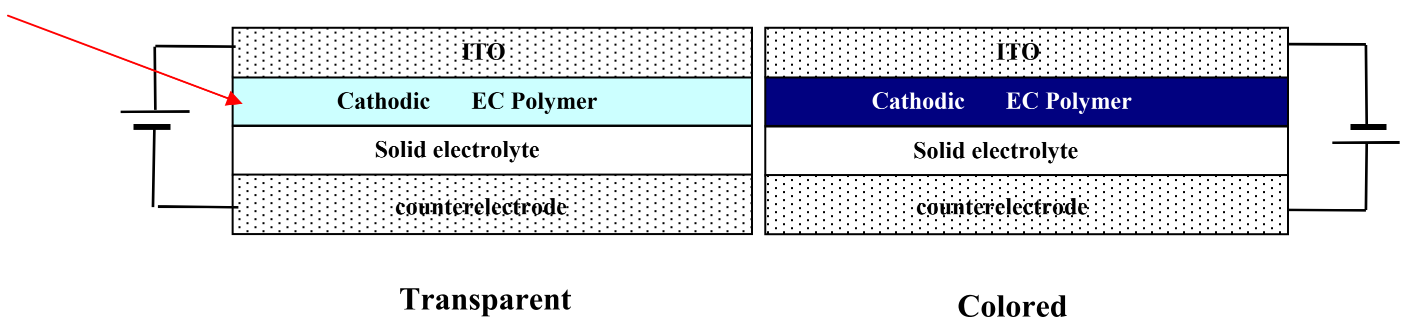
Au-patterned thin layer

Schematic diagram of device design using color changeable EC polymers

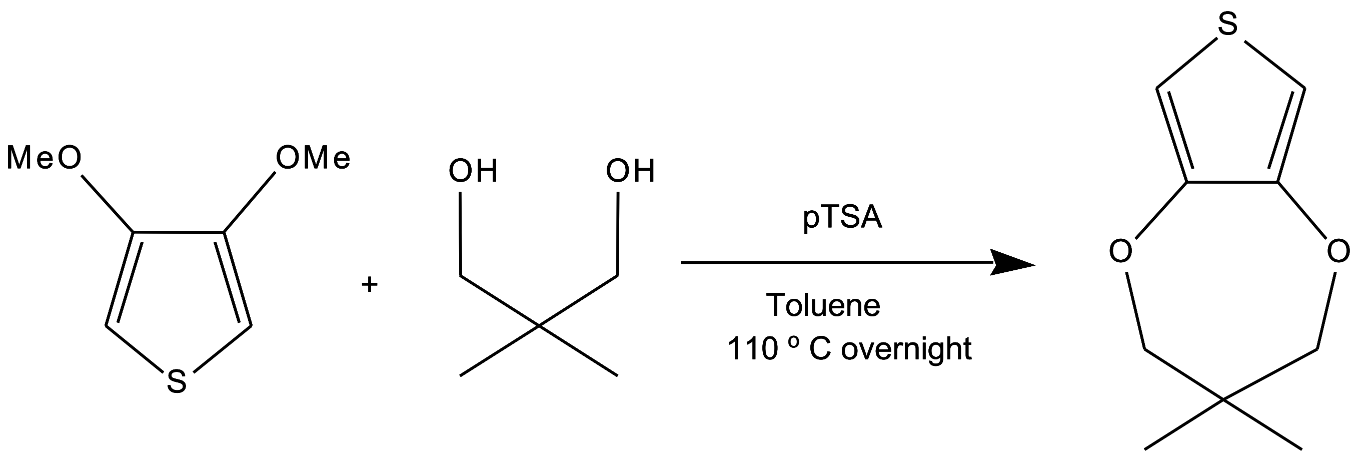
Three-layer scheme:

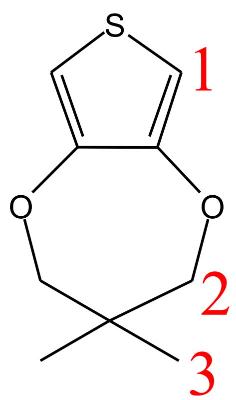


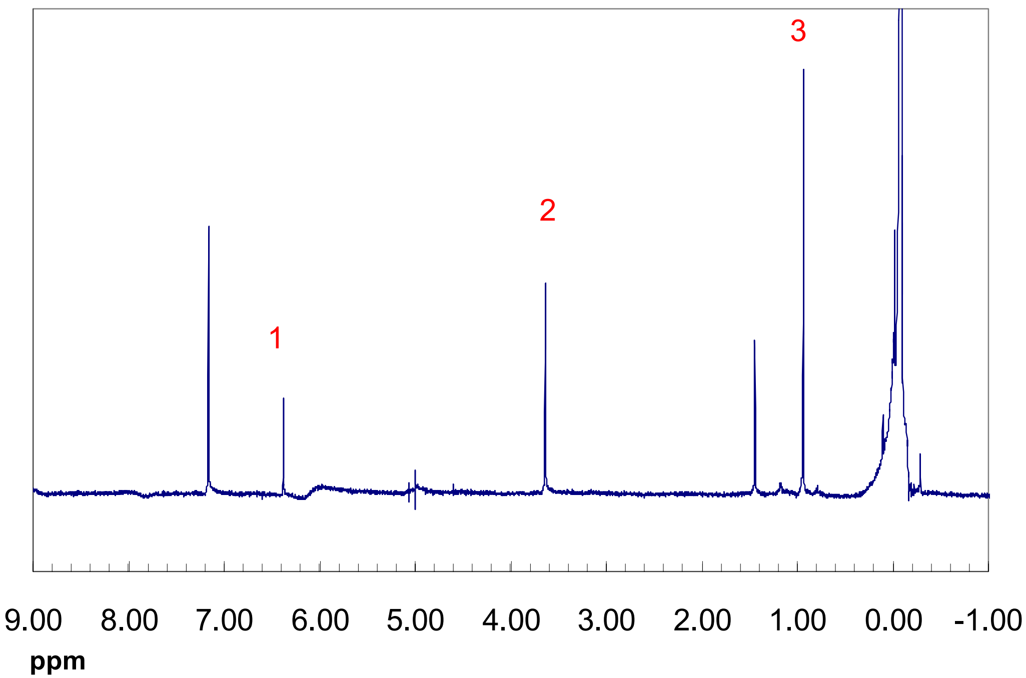
Two-layer scheme:



Synthetic Route of Monomer,ProDOT -Me 2 for Cathodic EC Polymer





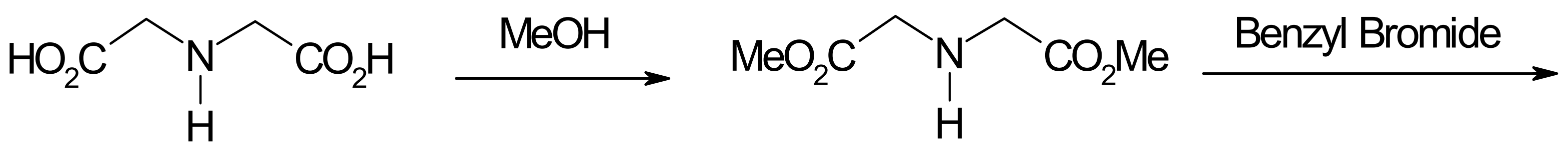


NMR spectra of cathodic monomer, ProDOT-$(CH_3)_2$

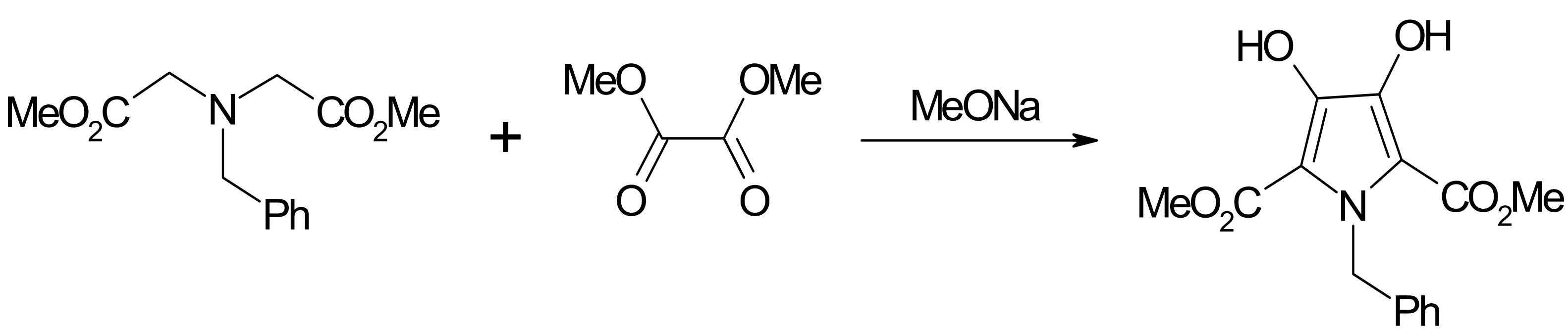
The number given over each NMR spectrum peak corresponds to the number given to the proton of ProDOT-$(CH_3)_2$ as shown in the left

Synthetic Route of EC Monomer, XDOP

-Benzylation of Dimethyl Iminodiacetate

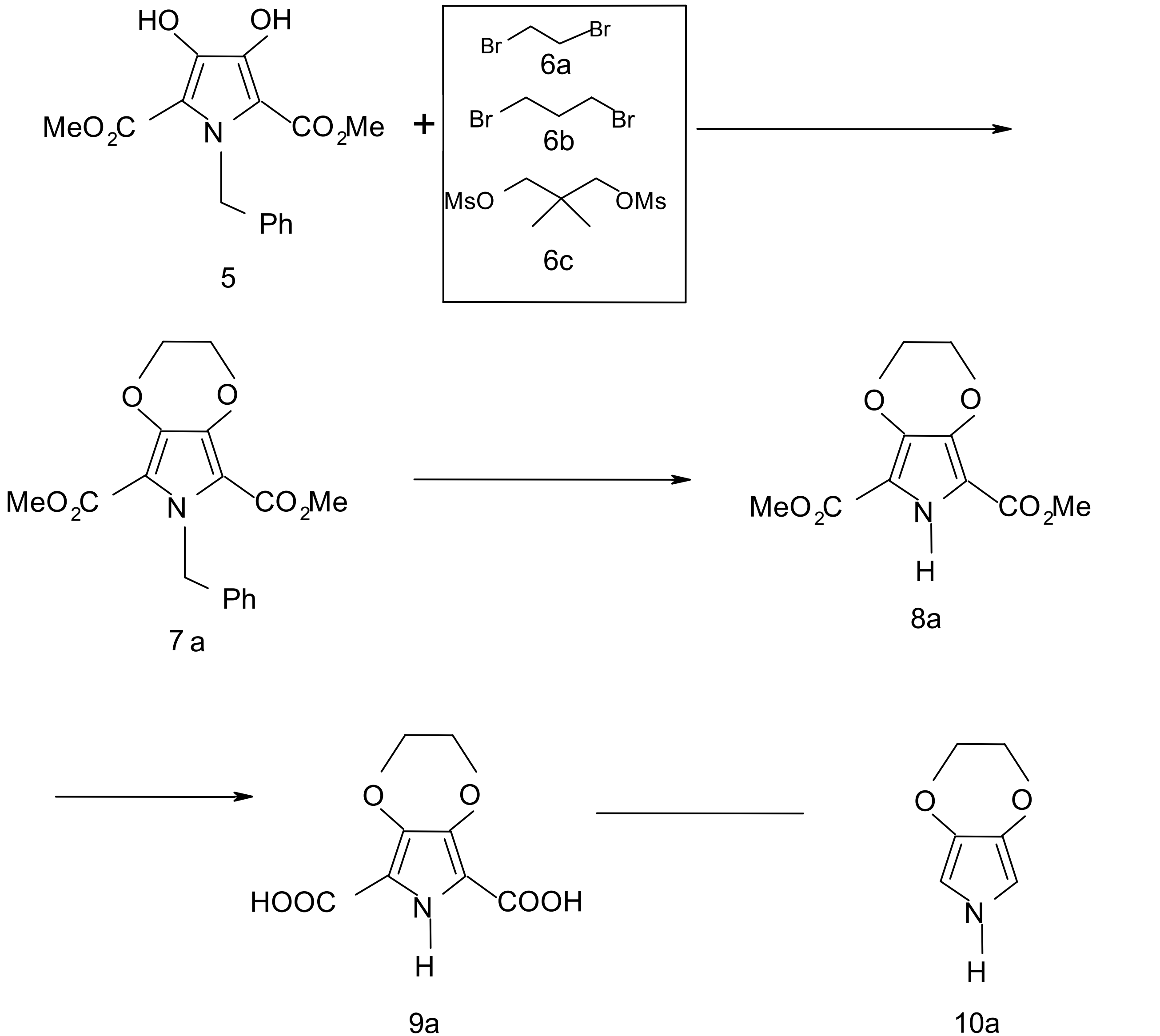


1 **2**

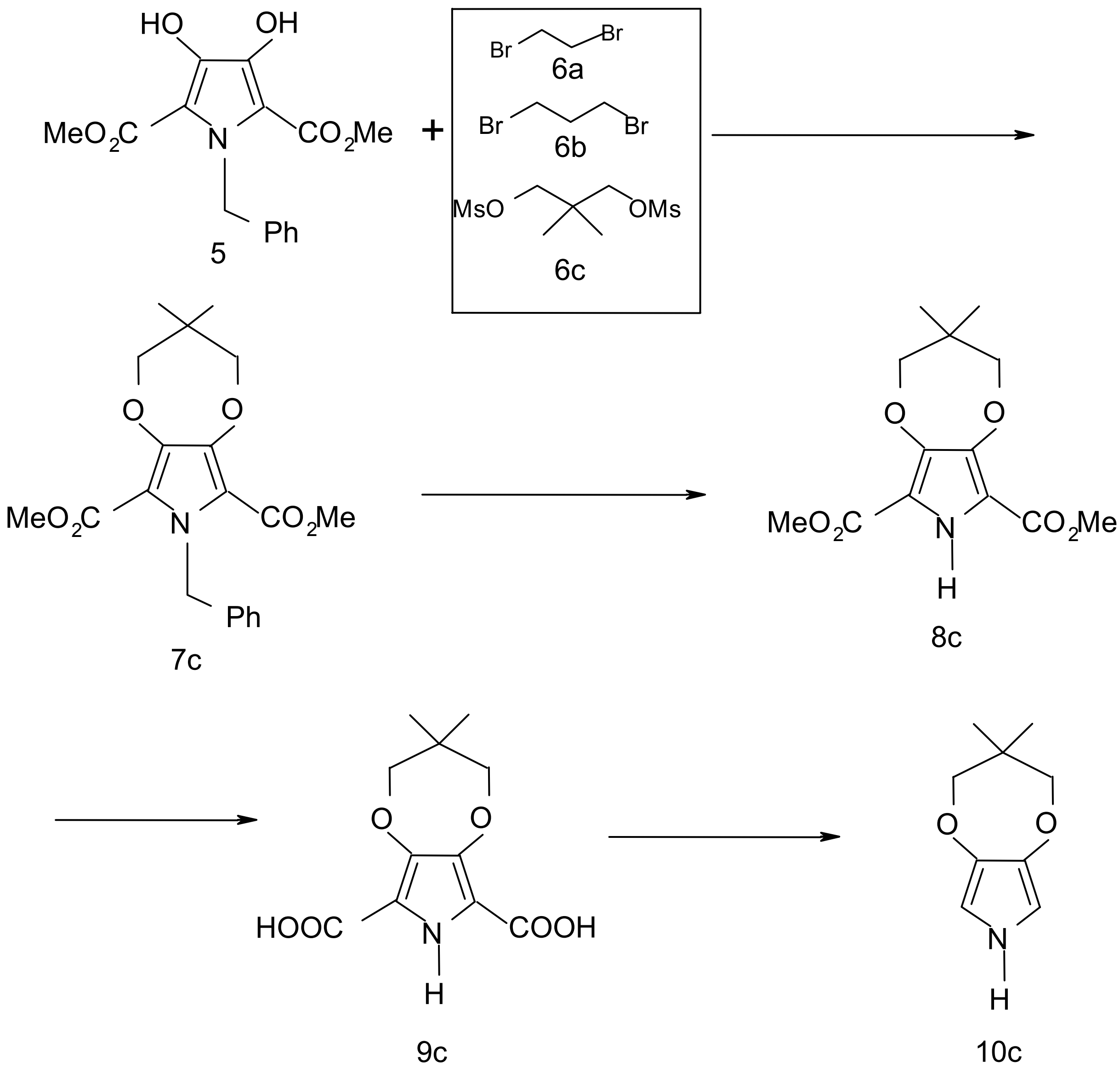


3 **4** **5**

Synthetic Route of EC Monomer, EDOP

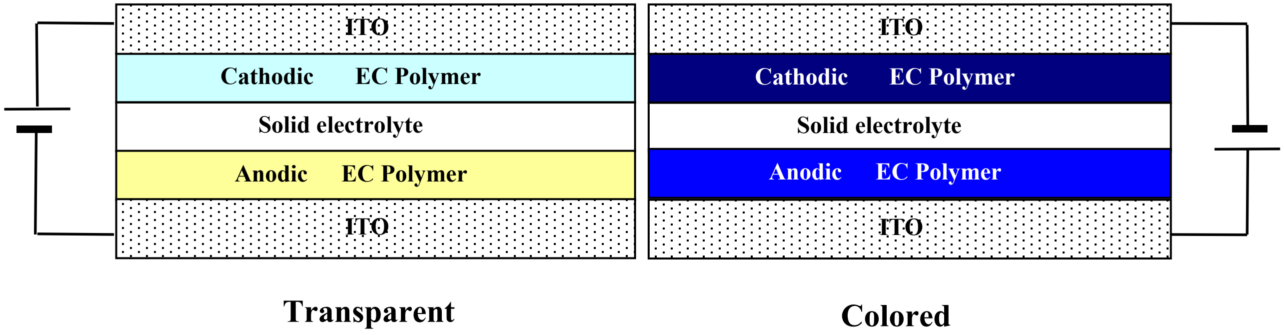


Synthetic Route of EC Monomer, ProDOP-$(CH_3)_2$

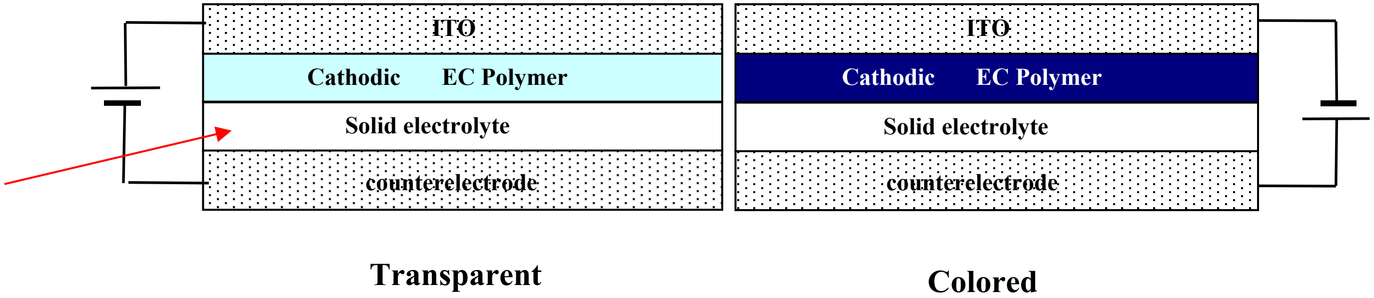


Schematic diagram of device design using color changeable EC polymers

Three-layer scheme:



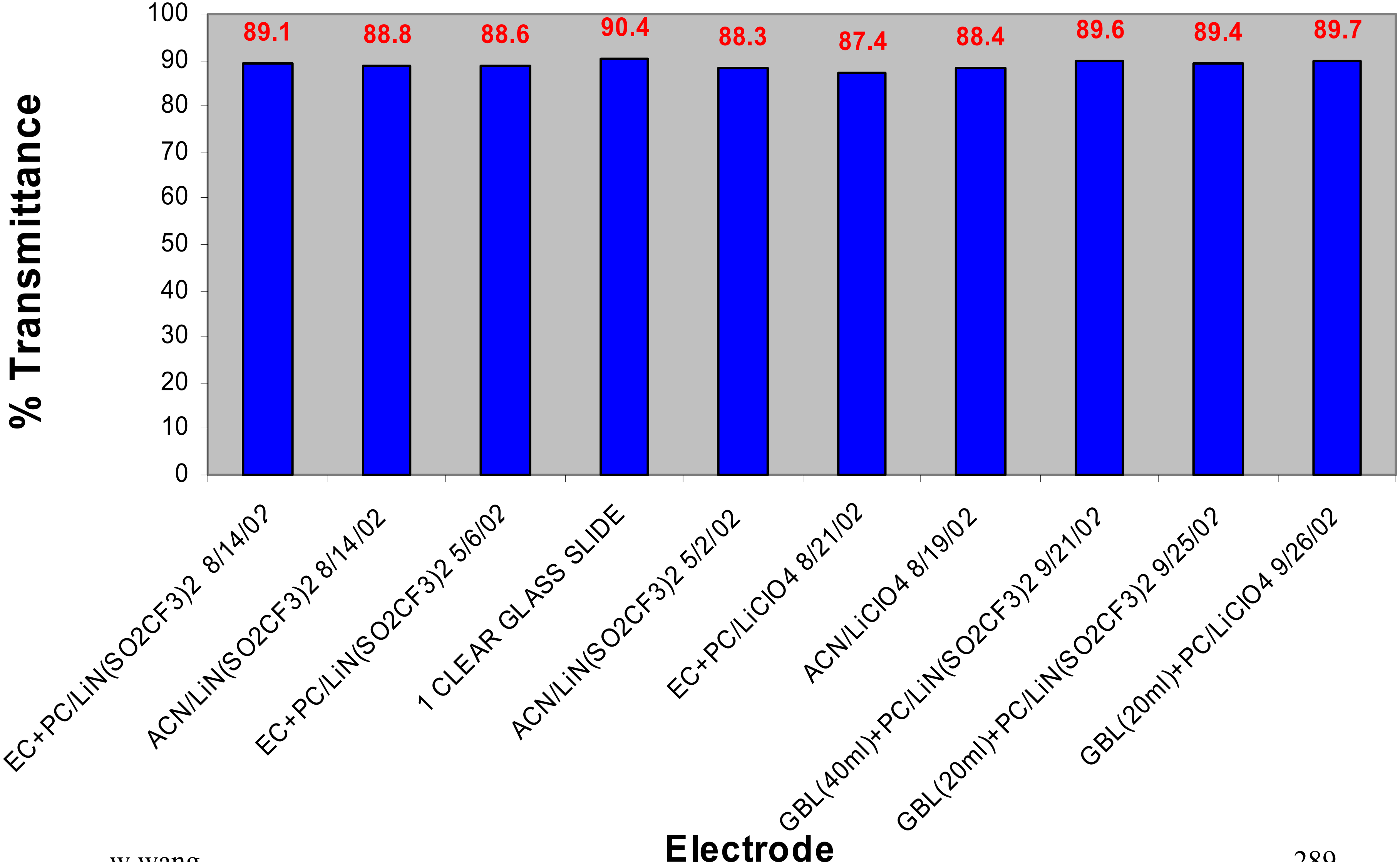
Two-layer scheme:



PMMA based gel electrolyte for EC smart windows

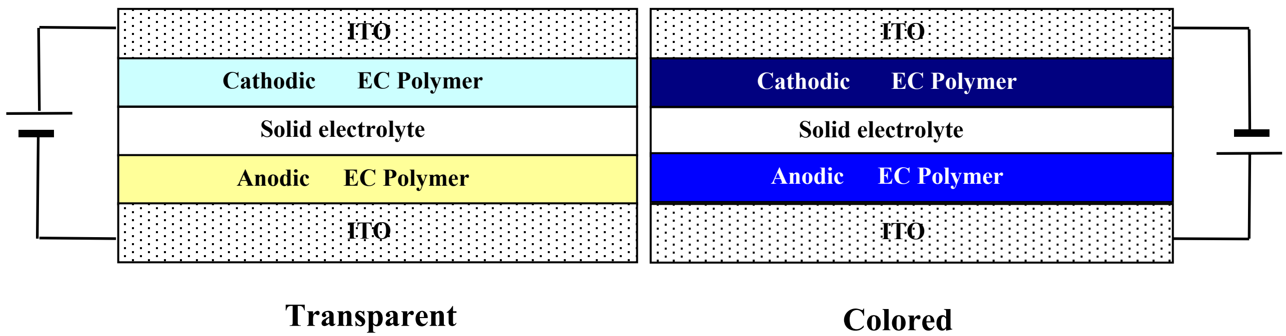
PMMA/LiN$(CF_3SO_2)_2$/PC wt% 20/10/70	PMMA/$LiClO_4$/PC wt% 20/10/70
PMMA/LiN$(CF_3SO_2)_2$/PC+EC wt% 20/10/70 (PC:EC=1:1 on volume)	PMMA/$LiClO_4$/PC+EC wt% 15/5/80 (PC:EC=1:1 on volume)

Transmittance of Indicated Gel Electrolyte

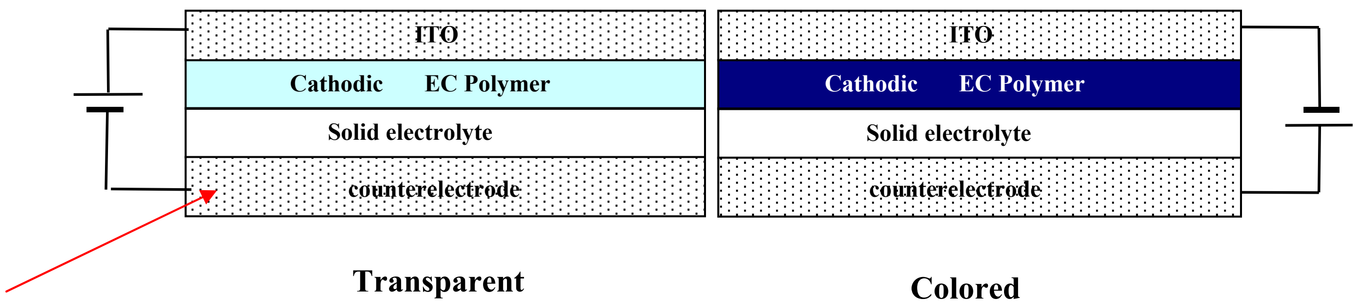


Schematic diagram of device design using color changeable EC polymers

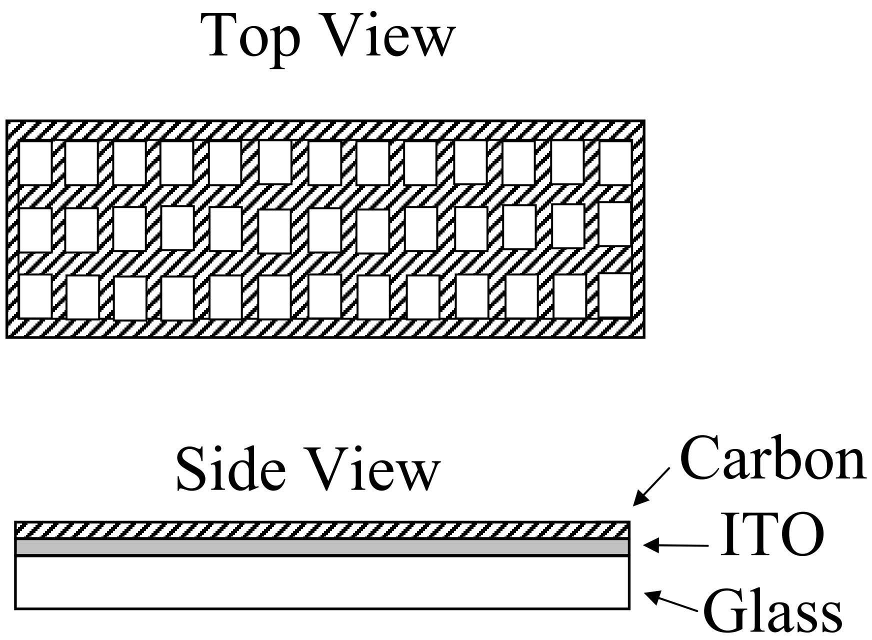
Three-layer scheme:



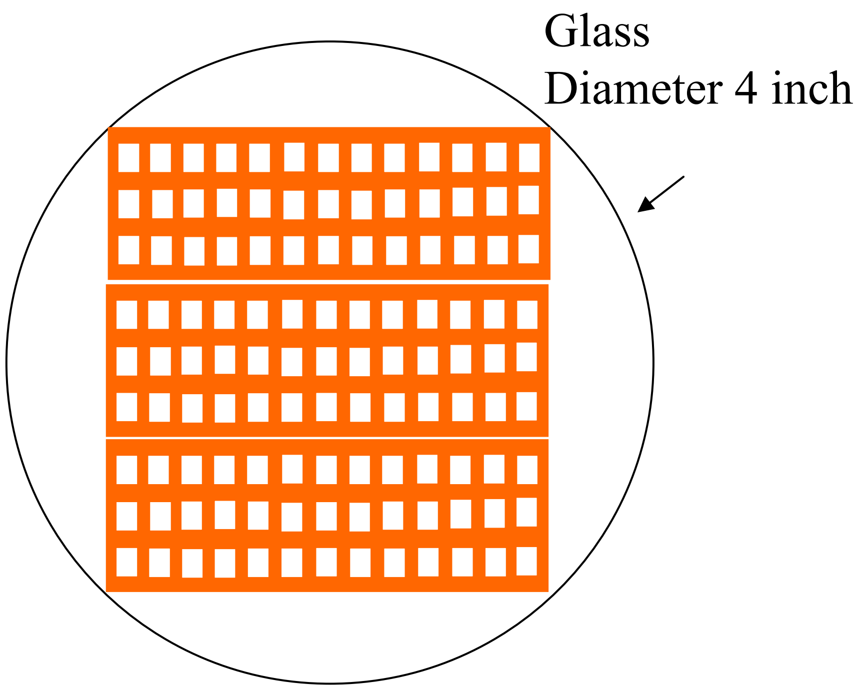
Two-layer scheme:



Design of Pattern for Carbon and Gold Based- Counterelectrode

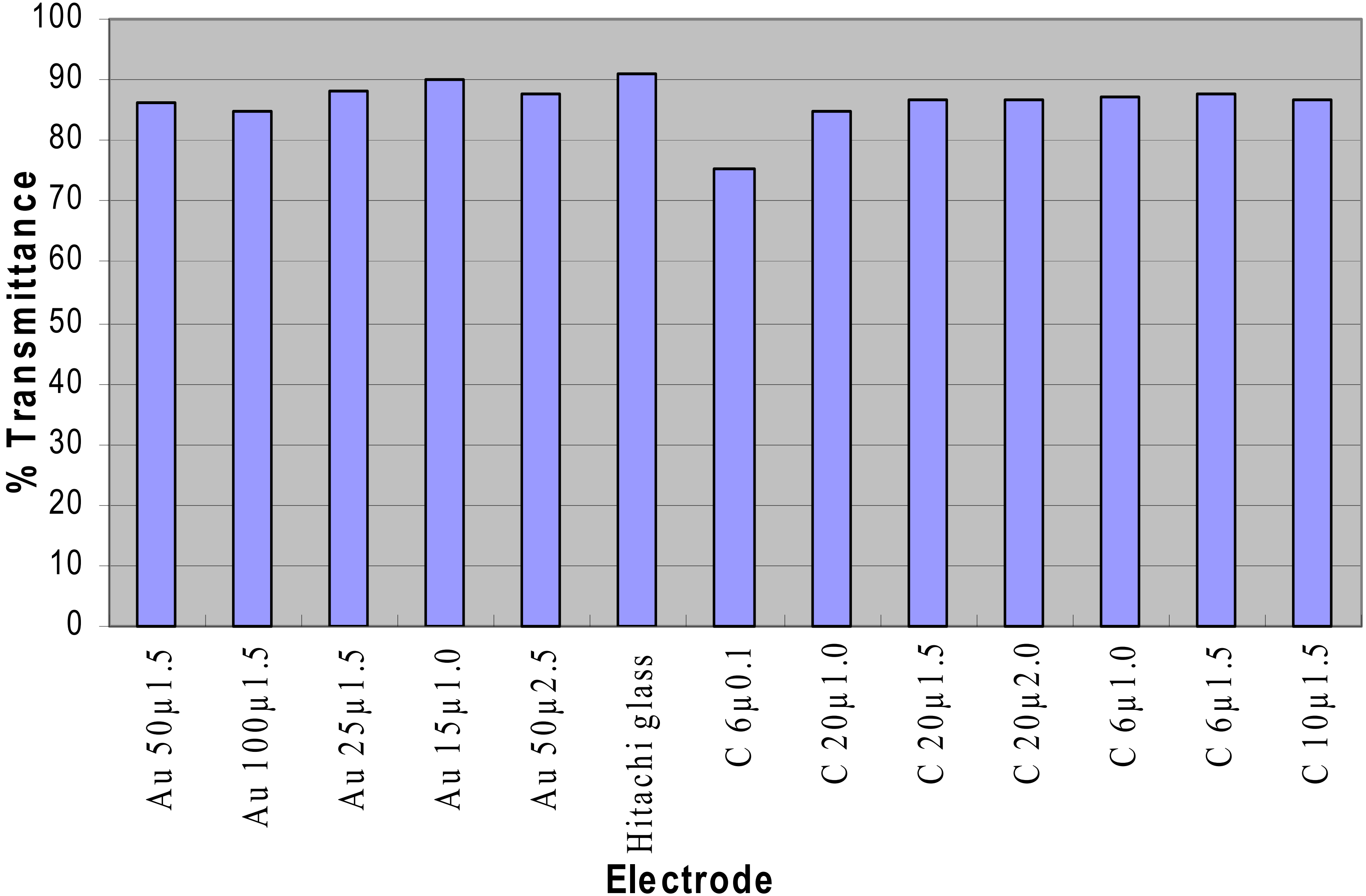


(a) Carbon-based

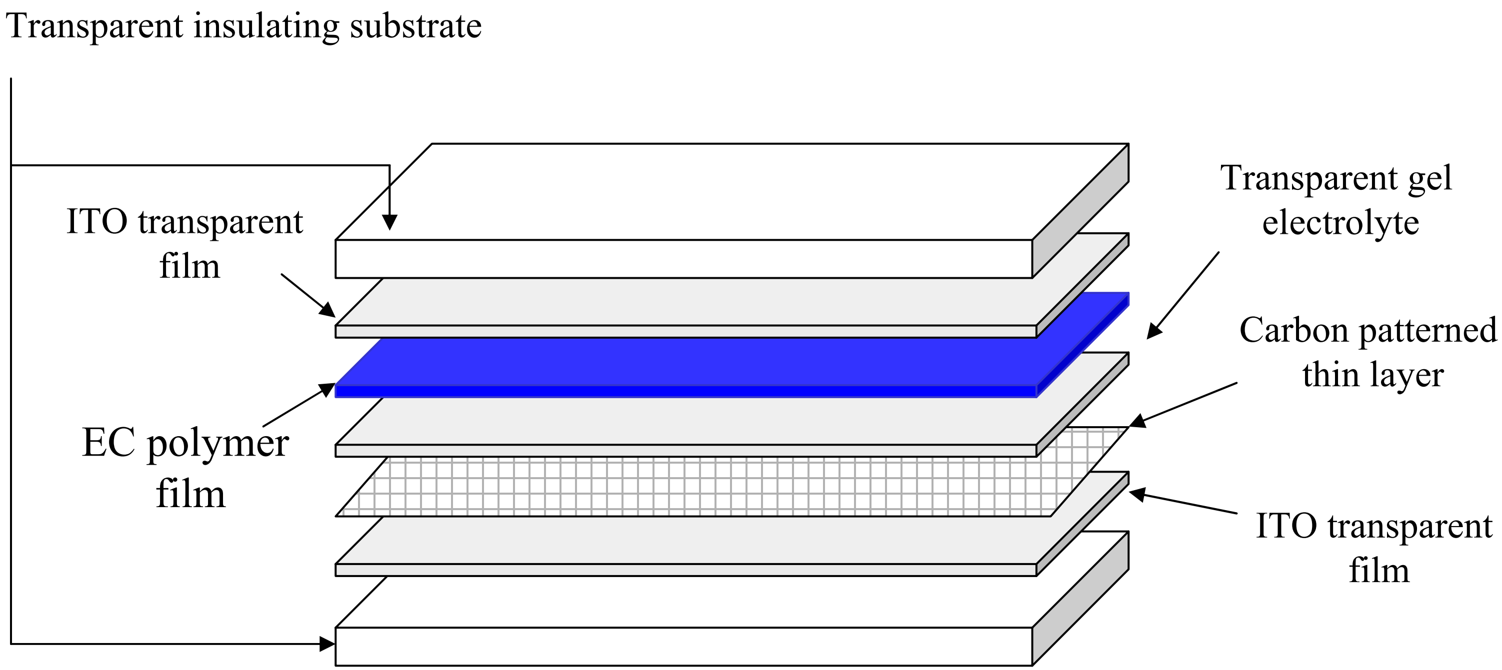


(b) Au-based

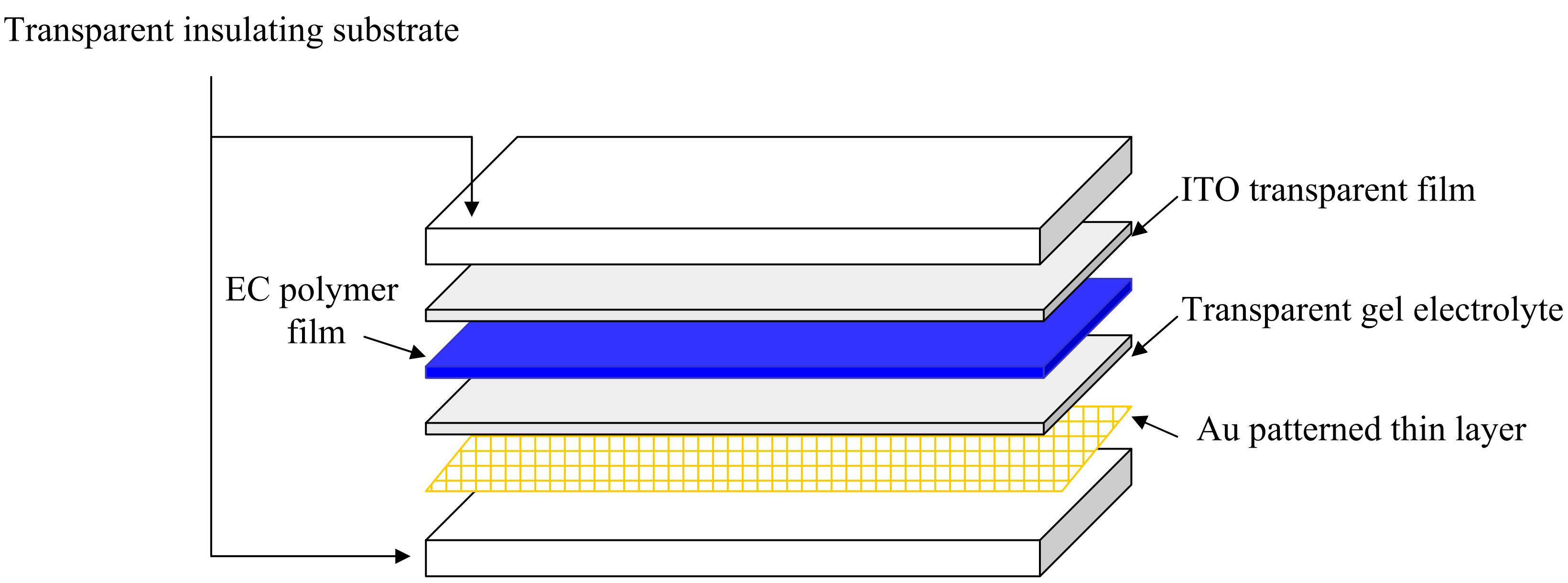
Transmittance of Indicated Electrode



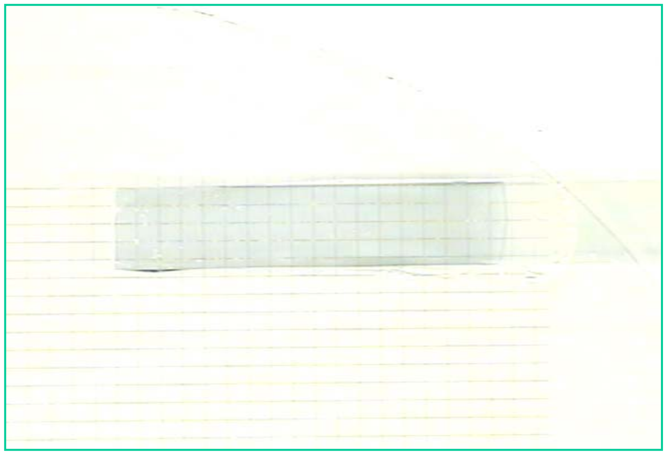
Assembly of EC polymer device for transmittance control in visible region, carbon-based counterelectrode



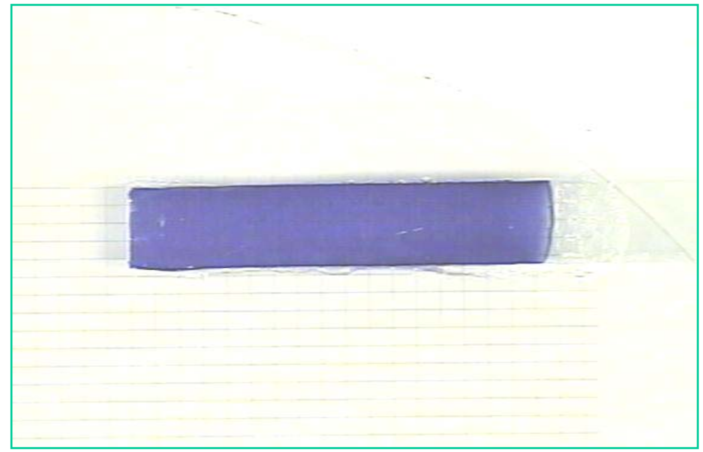
Assembly of EC polymer device for transmittance control in visible region, Au-based counterelectrode



Color Change of EC Polymer Device Using Au Patterned glass as a Counterelectrode



1s ⇄



(a) 2.5V, Transparent

(b) - 2.5V, Dark blue

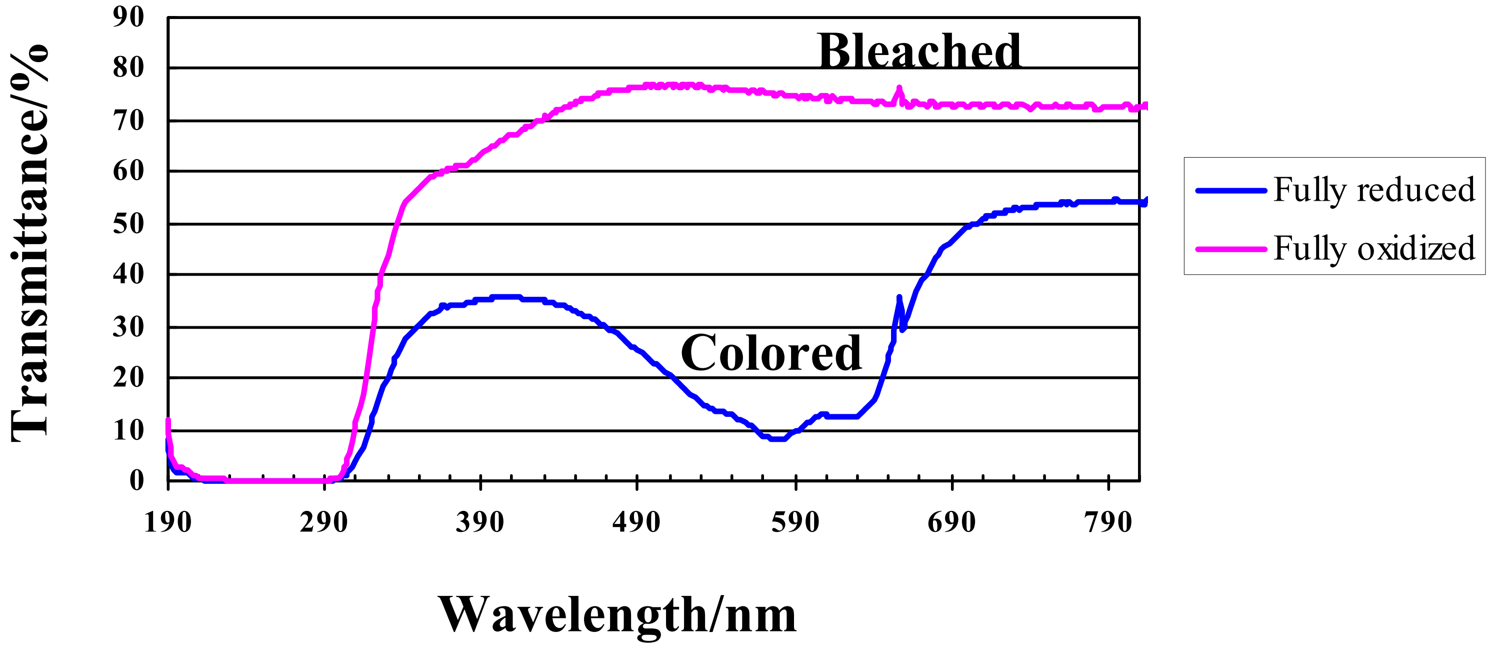
Color Change of EC Polymer Device Using Graphite Patterned ITO glass as a Counterelectrode

1s

(a) 2.5V, Transparent

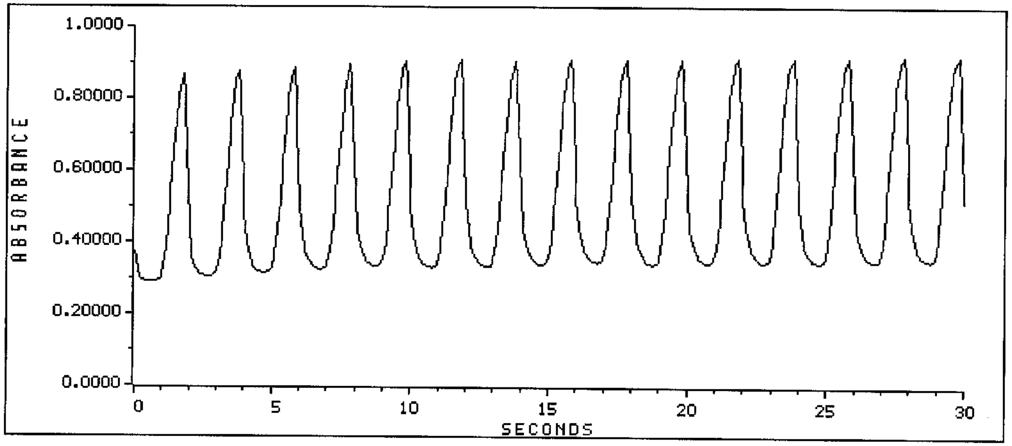
(b) - 2.5V, Dark blue

Enhanced Contrast Ratio in Cathodic EC Polymer Device Based on Au patterned counterelectrode

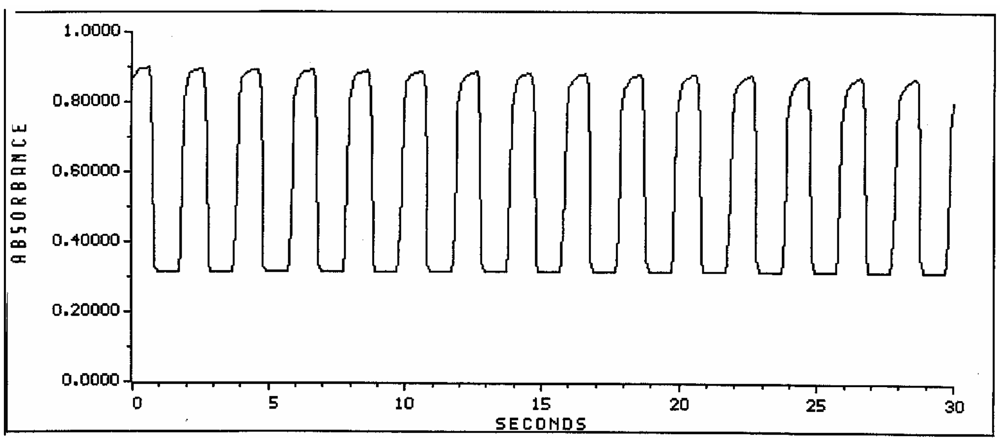


Visible spectrum collected in transmittance mode of a cathodic EC polymer device in fully transmitted and fully colored states

Enhanced Contrast Ratio and Rapid Switching in Cathodic EC Polymer Device



(a) Au-based

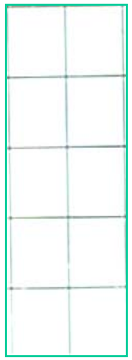


(b) Carbon-based

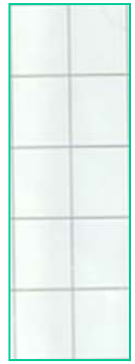
Optical switching for the devices based on indicated counterelectrodes monitored at wavelength 580nm

Photographs of potential effect on color changing degree

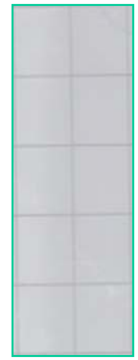
Blue EC polymer device/Gold counterelectrode



0V



-1.0V



-1.5V

-2.0V

- 2.5V

Red EC polymer/ ITO glass

-0.15V

-0.2V

-0.25V

-0.3V

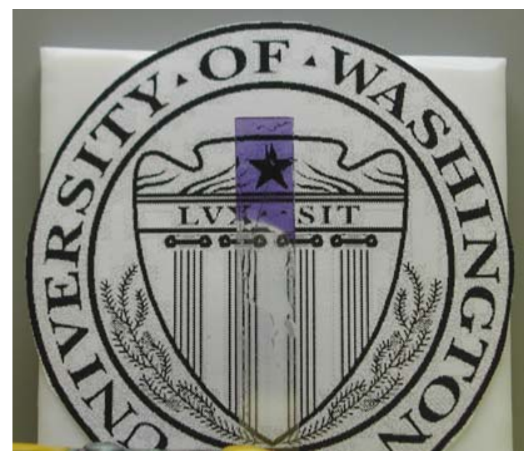
- 0.35V

Color changing speed is same, less than 1s

Blue EC Film Comparison

Or

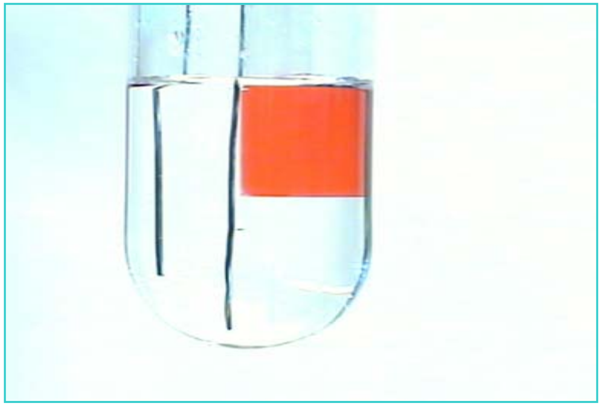
New Blue

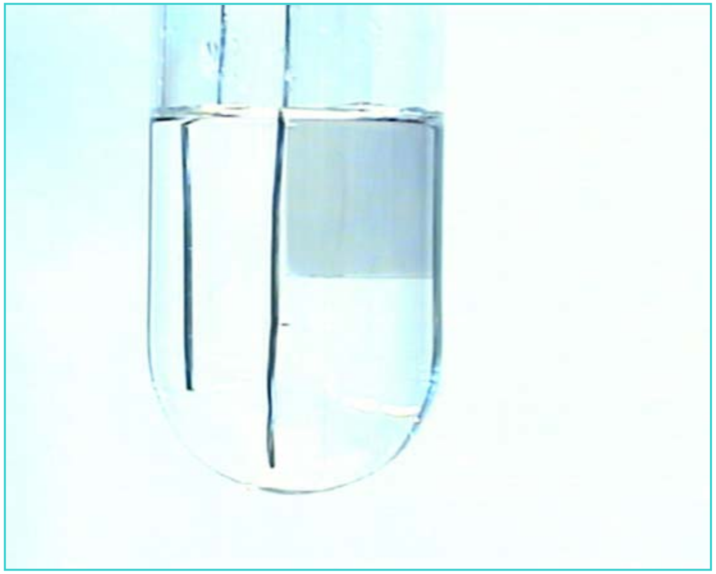


New red color

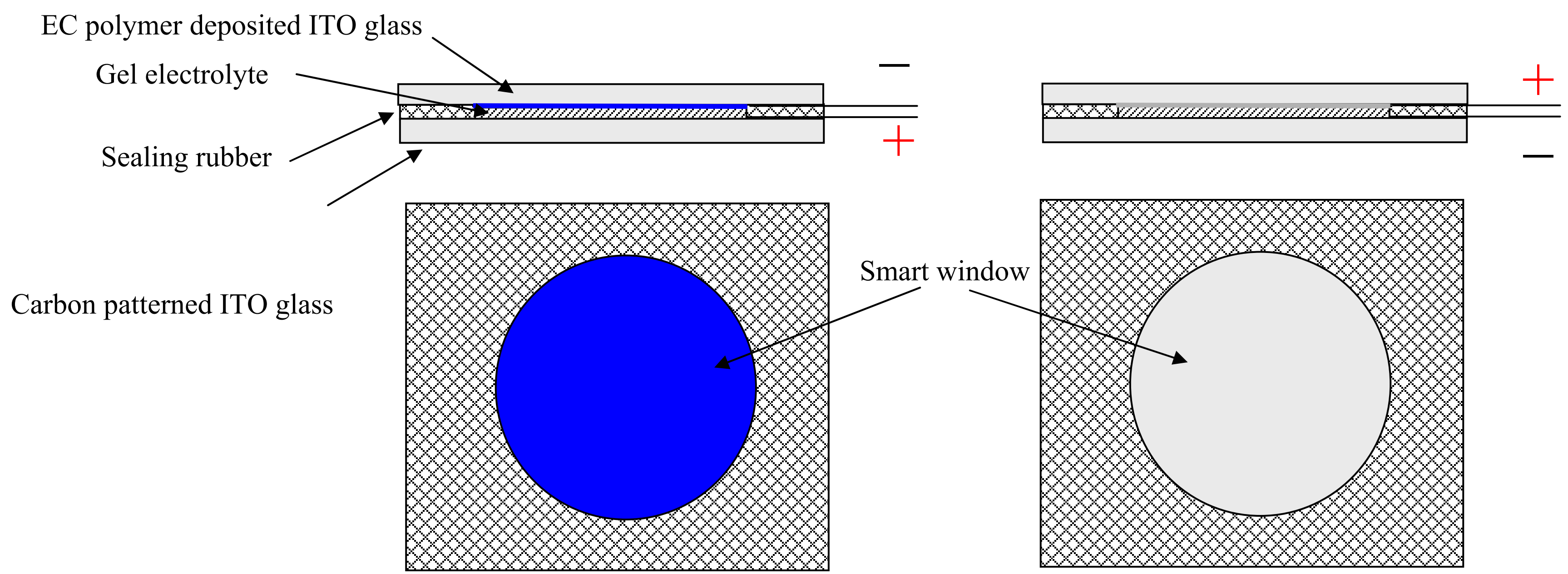
10a

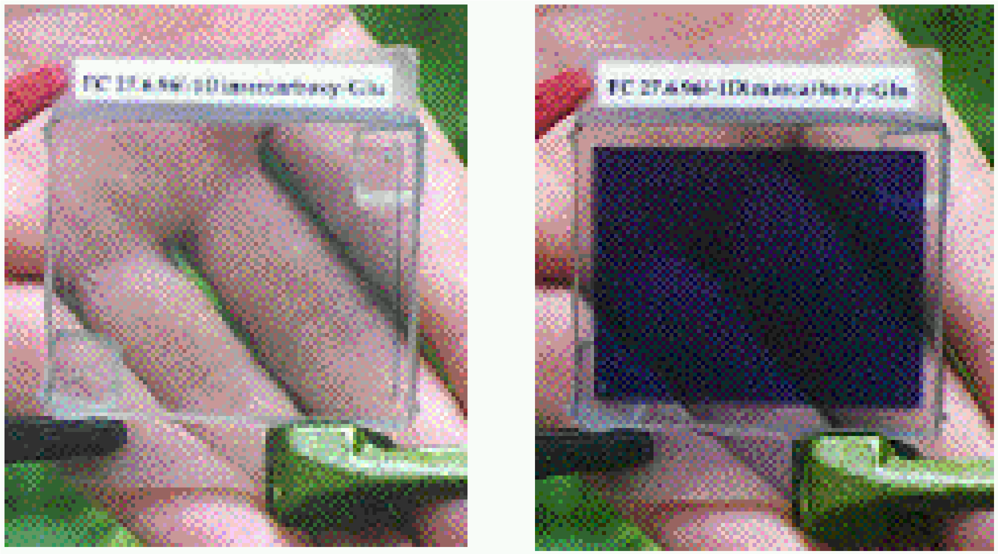
10c best



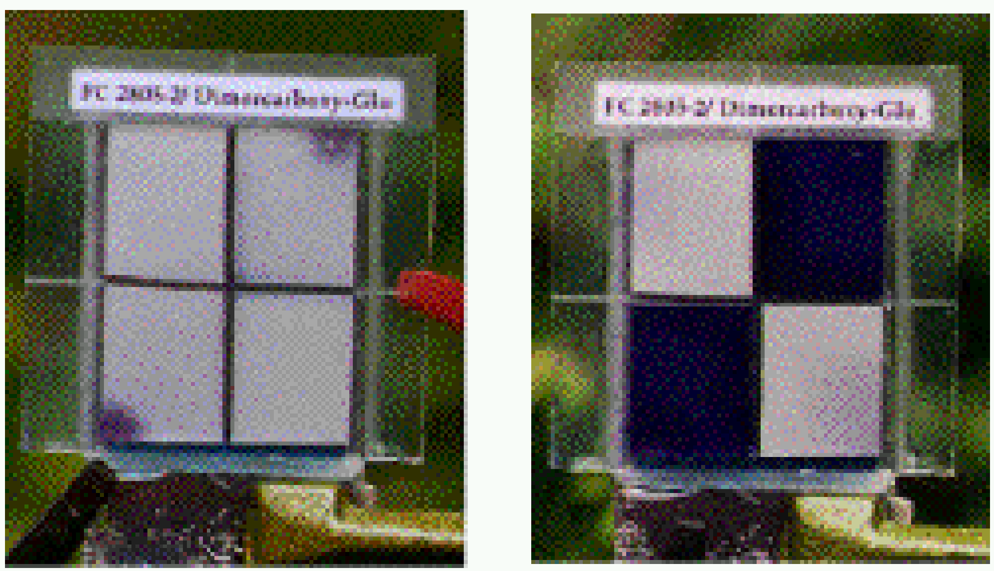


A circular smart window with rubber seal





An electrochromic window



A simple electrochromic display

Ishihara et al ,2001

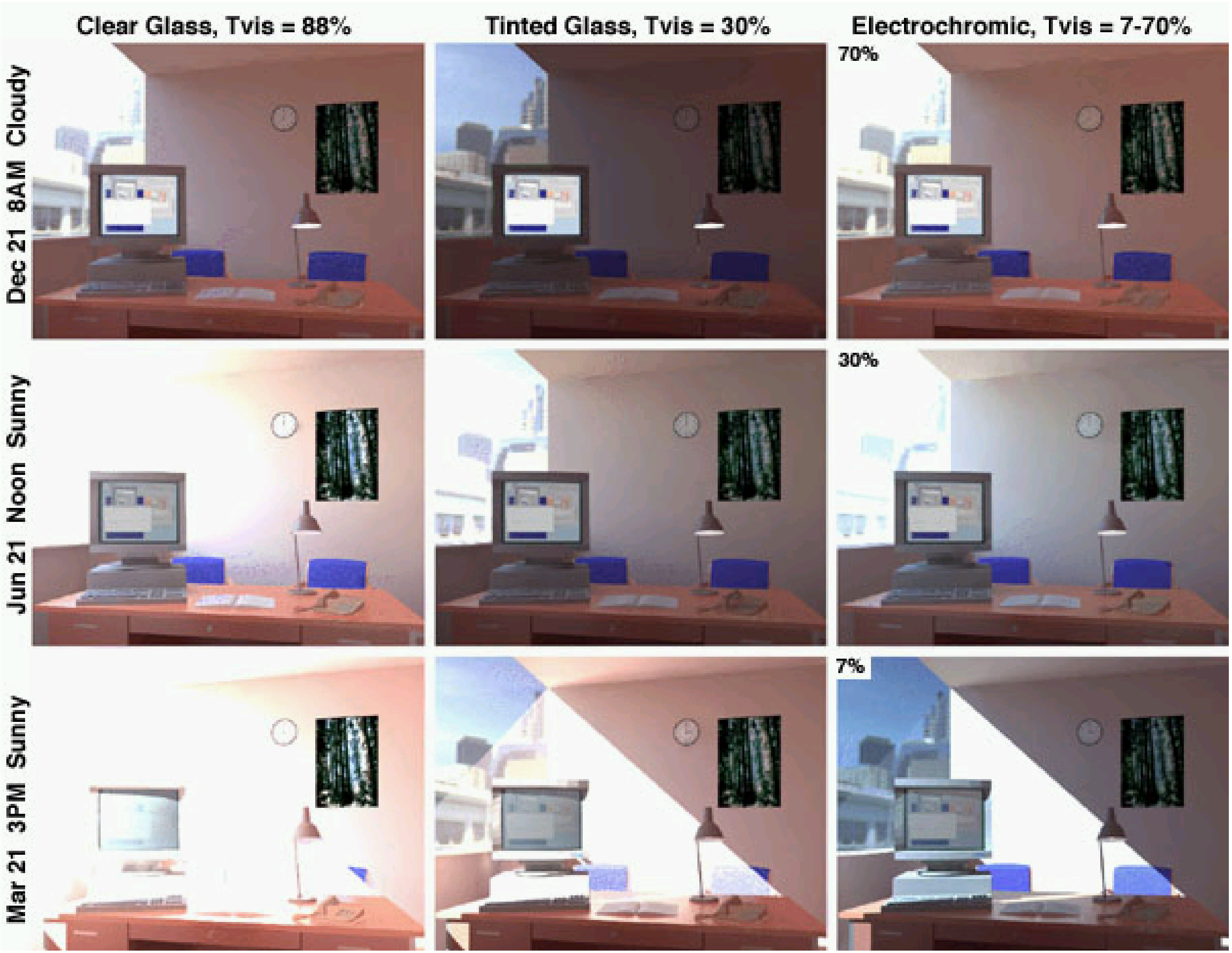
Application Potential

Commercial air plane

Special air craft

http://www.boeing.com

Smart window



w.wang

http://windows.lbl.gov/materials/chromogenics

Future works

Several new ideas…

1. Carbon nanotube actuator

2. Conducting polymer
- Bio-related actuator drug delivery system, e.g. polypyrrole
- Sensing clothing
  Body stress, signal, e.g. polyaniline(PANI) fiber

3. Special fiber

All-solid-state Electrochromic Glazing

WO_3, high durability but low contrast ratio (40:1)

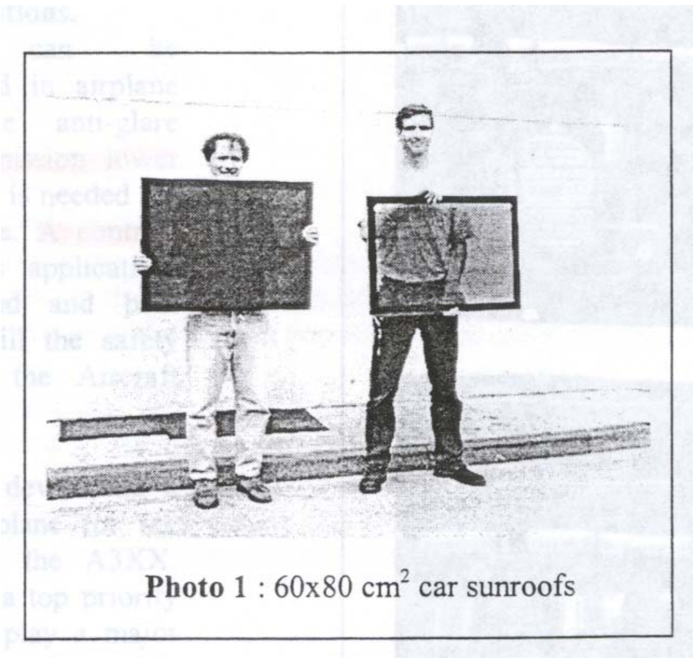
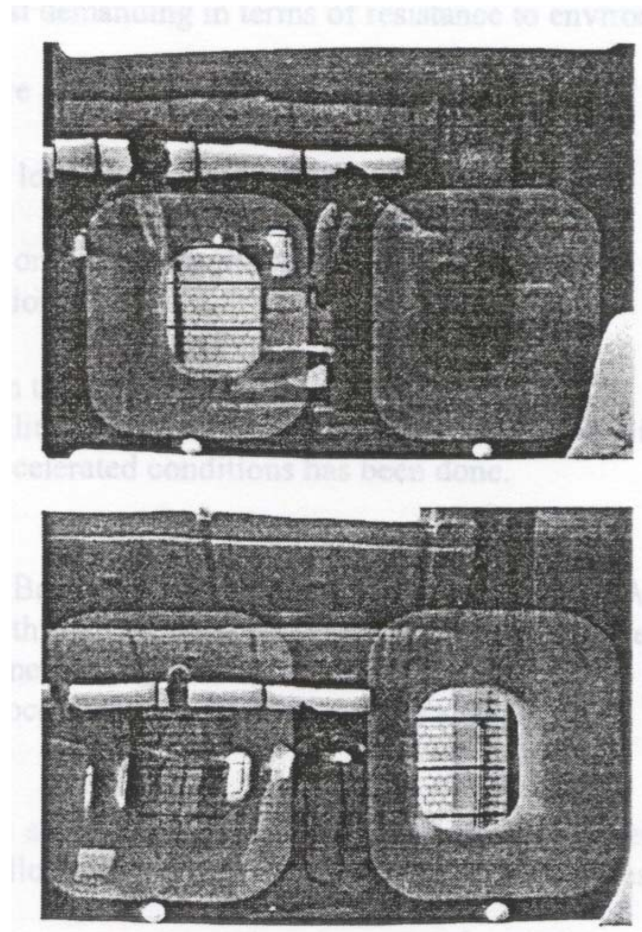


Photo 1 : 60x80 cm^2 car sunroofs



Aircraft side window

F. Beteille (France) The SPIE Conference on Switchable Materials and Flat Panel Displays
SPIE Vol. 3788 pp.70-73 (July 1999)

E-ink

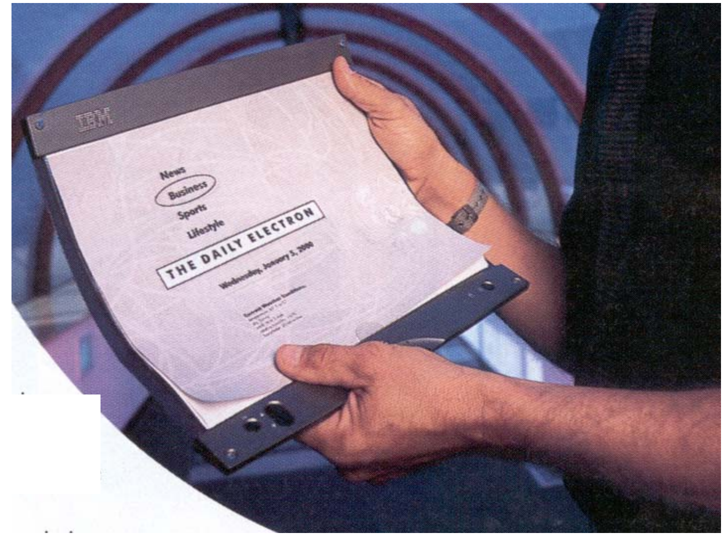
The Electronic

Digital "paper" that displays changing text and graphics would ideally marry the best features of traditional printed materials with those of video screens. Companies are racing to realize that promise using two competing technologies. Already retailers are testing cost-saving changeable e-ink signage.

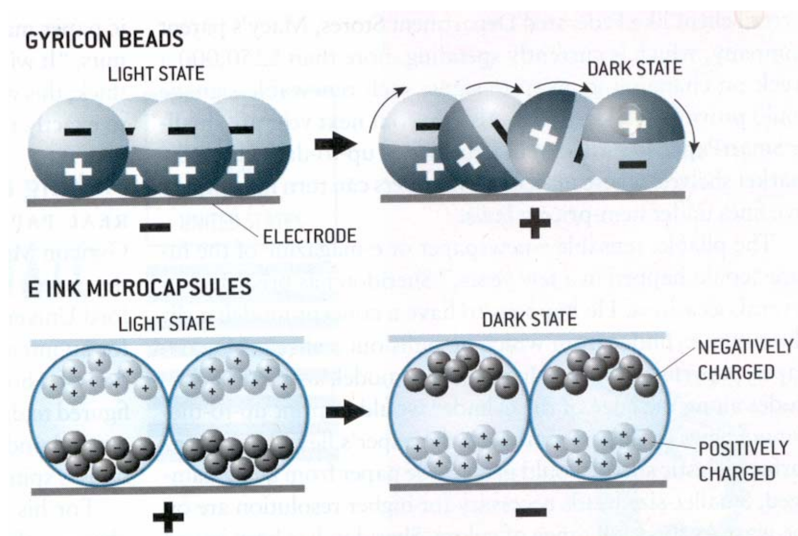
PAPER CHASE

Pliable, updatable e-newspapers, e-books and even an e-SCIENTIFIC AMERICAN could be here within a decade.

BY STEVE DITLEA

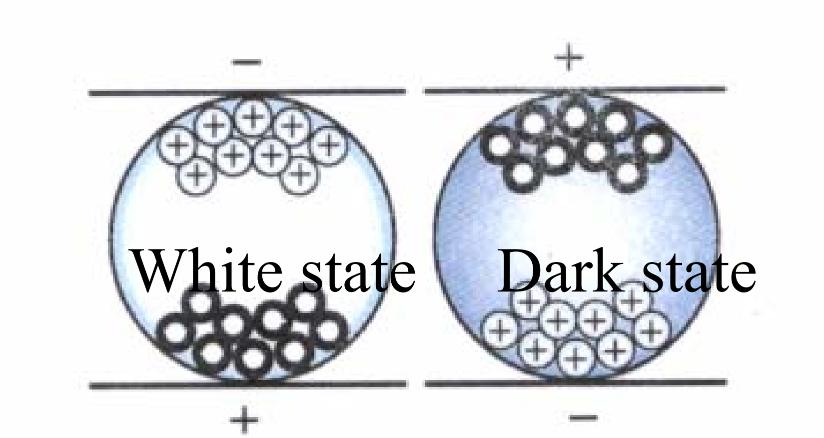


How they work?



Scientific American November 2001 pp,51-54

Flexible active-matrix electric ink display
- Electric paper



Nature 136 p.136 (2003)

Shape memory polymer

Camouflage skin of Octopus

Original

Camouflaged in white

Application potential

--- Wearable smart sensors/actuator

Day time
Land warrior

Day time
Taking a break

Night
Moving to the position

Conclusions

- From “hard” to “soft” technology
- EAP - structure, processing, sensing, actuation…
  …all in one
- Advantages for actuator applications:
  - light weight
  - energy storage
  - viscous damping
  - low cost
- Challenges:
  - Materials development
  - Integration into smart devices and structures