Department of Chemistry
University of Calicut

Course Title: Electroactive Polymers: Electrochemistry and Applications: Credits: 4 Cr

(Elective course for 9th Semester Integrated MSc and 3rd Sem MSc Chemistry)

Course Objectives

- Understand the chemistry and electrochemistry of electroactive polymers.
- Explain charge transport, redox processes, and ion transport in conducting polymers.
- Analyze electrochemical characterization techniques used for electroactive polymers.
- Explore applications in energy storage, sensing, actuators, soft robotics, and bioelectronics.

Course Outcomes (COs) : After completion of the course, students will be able to:

CO1: Explain the structure, synthesis, and charge transport mechanisms of electroactive polymers.
CO2: Interpret electrochemical behavior using modern electrochemical characterization techniques.
CO3: Design and evaluate electroactive polymer-based actuators, sensors, and energy storage devices.
CO4: Critically analyze current research trends and propose innovative applications of electroactive polymers.

UNIT I: Fundamentals of Electroactive Polymers (16 Hours)

Introduction: Classification of electroactive polymers, Electronic conducting polymers, Ionic electroactive polymers, Dielectric elastomers, Ionic Polymer Metal composites, EAP gels, Molecular EAP, Historcal development, Structure-property relationships

Conducting Polymers: Introduction, Polyaniline, Polypyrrole, PEDOT and EDOT:PSS, Polythiophene and derivatives, Structural characteristics. Origin of their conductivity; concept of doping and de-doping - p doping and N doping, charge transport and conducting mechanism, polarons, polarons, and solitons. Applications of conducting polymers. Chemical and electrochemical synthesis.

UNIT II: Electrochemistry of Electroactive Polymers (20 Hours)

Electrochemical Principles: Redox reactions, Faradaic and non-faradaic processes. Theories of Electrical double layer- Polarization, concentration polarization; Decomposition voltage and its determination; Over potential, Electrochemical Kinetics, Diffusion-controlled processes, Ion transport, Butler Volmer equation, Tafel equation. Tafel plot and its significance. Electro-chemo-mechanical coupling

Electrochemical Characterization: Cyclic voltammetry , Chronoamperometry , Chronopotentiometry Coulovoltammetry , Electrocheical impedance spectroscopy

Electrochemical Stability: Degradation mechanisms, Cycling stability, Self-discharge, Factors affecting electrochemical performance.

UNIT III: Electroactive Polymer Devices (16 Hours)

Electrochemical Actuators: Linear actuators, Bending actuators, Artificial muscles, Bilayer and trilayer actuators, Fiber and textile actuators

Sensors: Electrochemical sensors, Chemical sensors, Biosensors, Self-sensing actuators, Strain and pressure sensors

Device Fabrication: Thin films, nao and micro fibers, electrospinning, Hydrogels, Composite electrodes , 3D printing , Flexible electronics

Characterization: Actuation performance, Force generation, Response time , Efficiency and Durability.

UNIT IV: Emerging Applications and Future Directions (12 Hours)

Energy Applications: Supercapacitors, Rechargeable batteries, Hybrid energy storage , Flexible energy devices

Biomedical Applications: Drug delivery, Tissue engineering, Neural interfaces, Artificial muscles,

Soft Robotics: Biomimetic systems, Wearable electronics, Smart textiles, Human-machine interfaces

Emerging Trends: AI-assisted materials discovery, Multifunctional polymers, Sustainable electroactive polymers, Future challenges and commercialization.

Reference Textbooks

1. Wallace, G. G., Spinks, G. M., Kane-Maguire, L. A. P., & Teasdale, P. R. *Conductive Electroactive Polymers: Intelligent Polymer Systems*, 3rd Edition, CRC Press.
2. Otero, T. F. *Electrochemistry of Conducting Polymers: From Materials to Intelligent Devices*, Royal Society of Chemistry.
3. Skotheim, T. A., Reynolds, J. R. (Eds.). *Handbook of Conducting Polymers*, 3rd Edition, CRC Press.
4. Inzelt, G. *Conducting Polymers: A New Era in Electrochemistry*, Springer.
5. Bard, A. J., & Faulkner, L. R. *Electrochemical Methods: Fundamentals and Applications*, 2nd Edition.

UNIT I – Fundamentals of Electroactive Polymers

Contact hours: 12

1. What is an Electroactive Polymer?

An **electroactive polymer (EAP)** is a polymer that changes its size, shape, or electrical/optical properties in response to electrical stimulation, and conversely generates a measurable electrical signal when deformed. This two-way coupling between electrical and mechanical/chemical energy is what makes EAPs useful as actuators, sensors and charge-storage materials, often mimicking the behaviour of biological muscle.

2. Classification of Electroactive Polymers

EAPs are broadly grouped by the mechanism that produces the electroactive response:

Fig 1.1 Classification of Electroactive Polymers

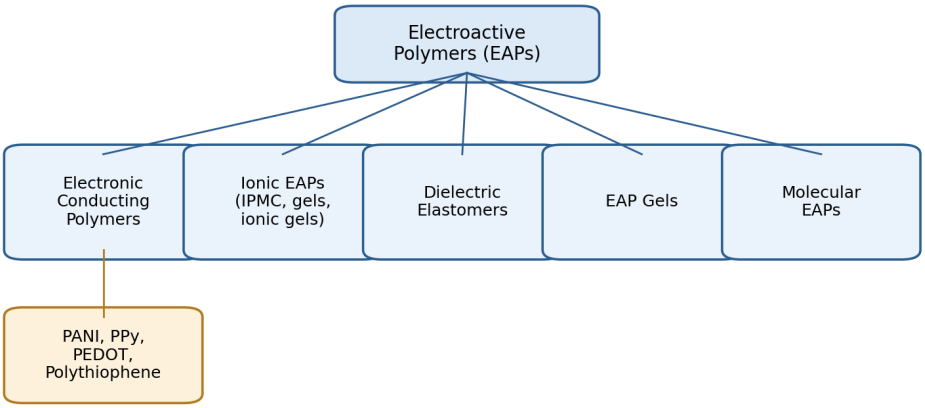

Fig 1.1 – Broad classification of electroactive polymers and examples of conducting polymers.

- **Electronic conducting polymers** – conjugated backbone (PANI, PPy, PEDOT, polythiophene) that conducts through delocalised pi-electrons after doping.
- **Ionic EAPs** – actuation driven by mobility of ions/solvent within the polymer (ionic polymer gels, conducting-polymer ionic actuators).
- **Dielectric elastomers** – a soft elastomer sandwiched between compliant electrodes deforms under an applied electric field (Maxwell stress effect); no redox chemistry involved.
- **Ionic Polymer–Metal Composites (IPMC)** – an ion-exchange membrane (e.g. Nafion) electroded on both faces with metal; ion migration under voltage causes bending.
- **EAP gels** – swelling/de-swelling of a polymer network driven by electrochemically generated pH or ionic-strength changes.
- **Molecular EAPs** – conformational change at the molecular level (e.g. redox-driven cis–trans isomerisation) transduced into macroscopic motion.

Historical note: the field began with the discovery in 1977 that polyacetylene could be doped to give near-metallic conductivity (Shirakawa, MacDiarmid, Heeger), work that was recognised with the 2000 Nobel Prize in Chemistry and opened the field of conducting polymers.

Structure-property relationship: conductivity and electroactivity in these polymers come from an uninterrupted, conjugated pi-system along the backbone. Any twist, cross-link, or saturated defect breaks conjugation and sharply lowers conductivity; hence processing conditions and chain regio-regularity strongly affect performance.

3. Conducting Polymers – Key Members

Fig 1.3 Repeat-unit sketches of common conducting polymers (schematic, not to scale)

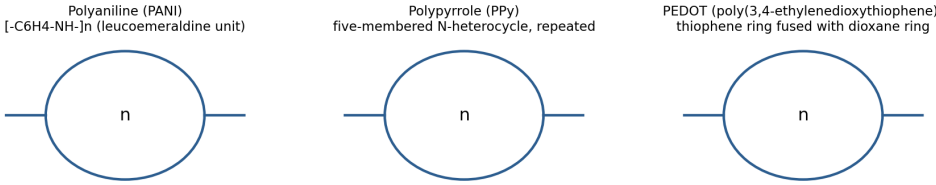

Fig 1.2 – Schematic repeat units of common conducting polymers (rings shown generically).

- **Polyaniline (PANI)** – exists in three oxidation states (leucoemeraldine, emeraldine, pernigraniline); the emeraldine salt (protonated with acid) is the conducting form. Low cost, tunable colour, but moderate environmental stability.
- **Polypyrrole (PPy)** – good environmental and aqueous stability, easily electropolymerised from pyrrole monomer; used widely in actuators and biosensors.
- **PEDOT and PEDOT:PSS** – the ethylenedioxy bridge blocks alpha-beta coupling defects, giving high conductivity and excellent stability; PEDOT:PSS (with polystyrene sulfonate as a water-soluble counter-ion/template) is the most widely used printable conducting polymer.
- **Polythiophene and derivatives** (e.g. P3HT) – side-chain engineering gives solution processability and is important in organic electronics and solar cells.

4. Origin of Conductivity: Doping

In the neutral state these polymers are semiconductors or insulators. Conductivity switches on through **doping** – a redox process (not atomic substitution as in inorganic semiconductors):

- **p-doping (oxidative doping):** the polymer backbone is oxidised (loses electrons); an anion from the electrolyte enters the film to balance the resulting positive charge.
- **n-doping (reductive doping):** the backbone is reduced (gains electrons); a cation from the electrolyte enters to balance the negative charge. n-doping is generally less stable in air/water.
- **De-doping** reverses either process, returning the polymer to its neutral, insulating state – this reversible switching is exactly what is exploited in electrochromic devices, actuators and batteries.

Fig 1.2 Formation of Polarons and Bipolarons on Oxidative (p-type) Doping

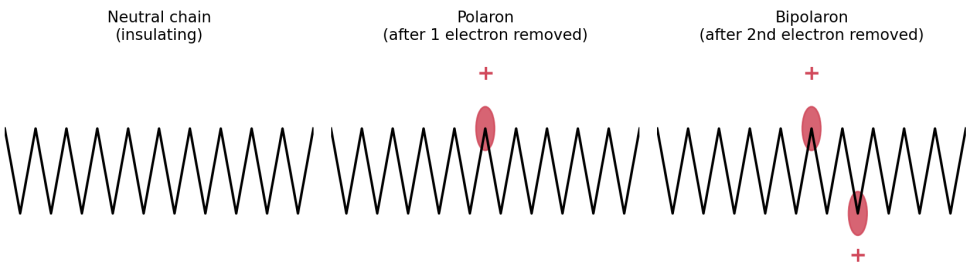

Fig 1.3 – Removing one electron creates a polaron (radical cation); removing a second nearby electron creates a spinless bipolaron. These charge carriers, not free electrons, transport charge along and between chains.

Charge transport mechanism: charge moves (i) along a chain by delocalisation of the polaron/bipolaron over several repeat units, and (ii) between chains/fibrils by interchain hopping. In heavily doped, ordered films the bipolarons can overlap to form a partly filled 'bipolaron band', giving metallic-like conduction. A soliton is a special, charge-neutral or charged domain-wall defect possible only in degenerate-ground-state polymers such as polyacetylene, where the two resonance structures are of equal energy.

5. Applications (Preview)

- Rechargeable battery and supercapacitor electrodes
- Electrochromic windows and displays
- Chemical/bio sensors
- Antistatic and EMI-shielding coatings
- Soft actuators and artificial muscles

6. Chemical and Electrochemical Synthesis

- **Chemical (oxidative) polymerisation:** monomer + chemical oxidant (e.g. FeCl3, ammonium persulfate) in solution; gives bulk powder, suited to large-scale production.
- **Electrochemical polymerisation:** monomer solution is oxidised at an electrode by an applied anodic potential/current; the polymer deposits directly as a film on the electrode, allowing precise control of thickness and doping level – the method of choice for making devices directly.

Quick recap: EAPs are classified by their actuation mechanism; conducting polymers owe their conductivity to reversible redox doping that creates mobile polarons/bipolarons along a conjugated backbone; both chemical and electrochemical routes are used to make them, with electropolymerisation preferred for device fabrication.

UNIT II – Electrochemistry of Electroactive Polymers

Contact hours: 12

1. Electrochemical Principles

Electrochemical reactions involve electron transfer at an electrode/electrolyte interface. A **Faradaic process** involves actual charge transfer across the interface (a redox reaction, obeying Faraday's law: charge passed is proportional to moles reacted). A **non-Faradaic process** involves no charge crossing the interface – instead charge simply rearranges at the interface, as in charging of the electrical double layer. Both processes occur simultaneously at a real electrode and both contribute to the measured current.

1.1 Electrical Double Layer (EDL)

When an electrode is polarised, ions and solvent dipoles near the surface organise into a structured region called the electrical double layer. The classical Gouy–Chapman–Stern picture divides it into (i) the **Stern (compact) layer** of ions specifically adsorbed or held at the plane of closest approach, and (ii) the **diffuse layer**, where ion concentration decays into the bulk following a Boltzmann-type distribution. This structure behaves electrically like a capacitor and underlies both non-Faradaic double-layer charging and the operating principle of electrochemical (double-layer) supercapacitors.

Fig 2.1 Electrical Double Layer at a Polarized Electrode

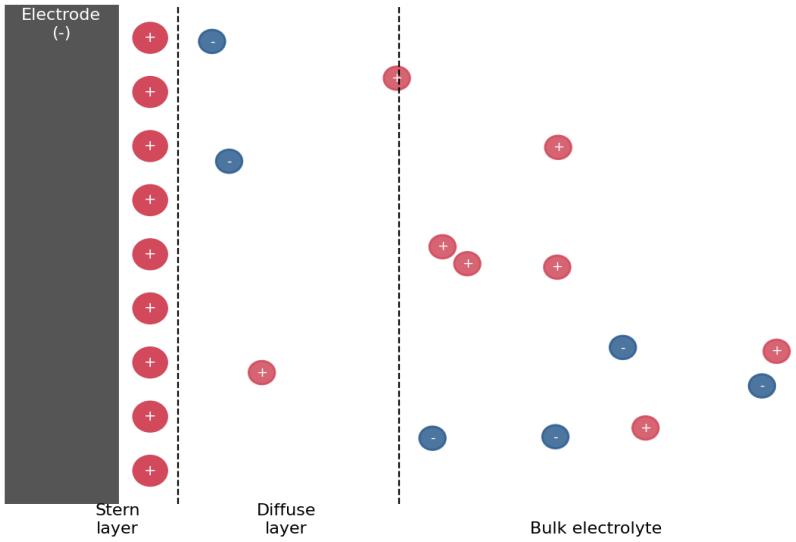

Fig 2.1 – Structure of the electrical double layer: an ordered Stern layer next to the electrode, followed by a diffuse layer that merges into bulk electrolyte.

1.2 Polarization and Decomposition Voltage

- **Polarization** is the deviation of electrode potential from its equilibrium value when current flows; it has activation, ohmic and concentration contributions.
- **Concentration polarization** arises when the electrode reaction consumes reactant faster than it can diffuse from bulk solution, depleting the interfacial concentration and shifting the potential.
- **Decomposition voltage** is the minimum applied voltage at which continuous electrolysis (bulk decomposition) begins; it is found experimentally from the point where current starts rising sharply in a current–voltage plot, and includes the thermodynamic reversible potential plus the total overpotential needed to drive the reaction at a measurable rate.

- **Overpotential** is the extra potential, beyond the equilibrium value, needed to drive a given current – it quantifies the kinetic 'cost' of the reaction and includes activation, concentration and ohmic (iR) components.

2. Electrochemical Kinetics

The rate of an electrode reaction depends exponentially on overpotential. This relationship is captured by the **Butler–Volmer equation**, which expresses net current density as the difference between forward (cathodic) and backward (anodic) partial current densities, each depending exponentially on overpotential through a transfer coefficient. At large overpotential (either sign), one exponential term dominates and the Butler–Volmer equation reduces to the **Tafel equation**, which gives a linear relationship between overpotential and the logarithm of current density.

- A **Tafel plot** (overpotential vs. log current) is linear in the high-overpotential region; its slope (the Tafel slope) reveals the rate-determining step and reaction mechanism, and extrapolation to zero overpotential gives the exchange current density – a measure of the intrinsic rate of electron transfer at equilibrium.
- **Diffusion-controlled processes:** when electron transfer itself is fast, the overall rate becomes limited by how quickly reactant/product diffuses to and from the electrode; this regime is described by Fick's laws and gives rise to the characteristic peak-shaped or sigmoidal responses seen in voltammetry.
- **Ion transport in the polymer film** itself (not just in solution) is often the actual rate-limiting step for conducting polymers, since dopant ions must move into/out of the bulk film to maintain electroneutrality as the redox state changes.
- **Electro-chemo-mechanical coupling** describes how the redox-driven insertion/expulsion of ions and solvent changes the polymer's volume, producing the swelling/bending actuation strain; this coupling is central to how EAP actuators and self-sensing elements work.

3. Electrochemical Characterization Techniques

3.1 Cyclic Voltammetry (CV)

The electrode potential is swept linearly between two limits and back while current is recorded. Peaks appear where a redox reaction occurs; peak position, shape and separation give information on redox potential, reversibility and reaction rate, while peak current usually scales with the square root of scan rate for a diffusion-controlled process (or linearly with scan rate for a surface/thin-film-confined process, as is common for conducting polymer films).

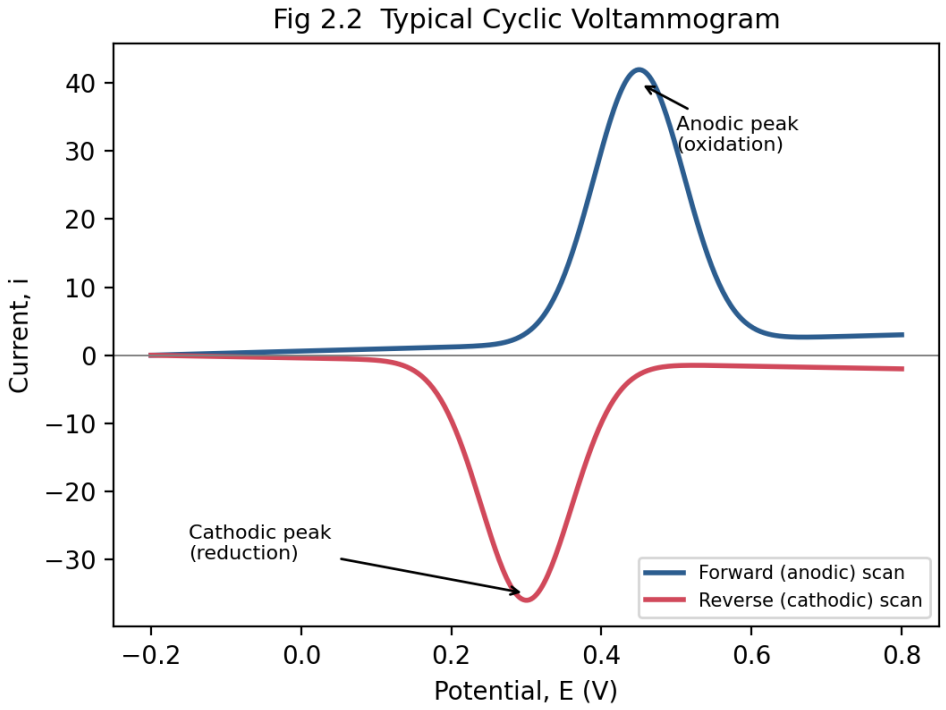

Fig 2.2 – Idealised cyclic voltammogram showing anodic (oxidation) and cathodic (reduction) current peaks on the forward and reverse potential scans.

3.2 Chronoamperometry and Chronopotentiometry

- **Chronoamperometry:** a potential step is applied and the resulting current is monitored versus time; the decaying current reflects the changing rate of the electrode reaction and, in a diffusion-limited case, follows the Cottrell relationship (current proportional to 1 divided by the square root of time).
- **Chronopotentiometry:** a constant current is applied and the resulting potential is monitored versus time; a plateau followed by a sharp potential change (the 'transition time') marks depletion of the reactant or complete charging/discharging of the film – this method is routinely used to measure the charge-storage capacity and coulombic efficiency of EAP electrodes.
- **Coulovoltammetry** combines charge (coulometric) integration with the voltammetric scan, tracking the total charge passed as a function of potential; it is particularly useful for quantifying the amount of redox-active polymer and its doping level.

3.3 Electrochemical Impedance Spectroscopy (EIS)

A small-amplitude AC potential (over a wide frequency range) is applied and the current response is measured to extract the complex impedance at each frequency. Results are commonly plotted as a **Nyquist plot** (imaginary vs. real impedance): a semicircle at high-to-mid frequency reflects charge-transfer resistance in parallel with double-layer capacitance, while a straight line at low frequency (close to 45°) reflects diffusion (Warburg impedance) of ions within the film. Fitting the spectrum to an equivalent circuit extracts solution resistance, charge-transfer resistance, double-layer/pseudocapacitance and diffusion parameters separately.

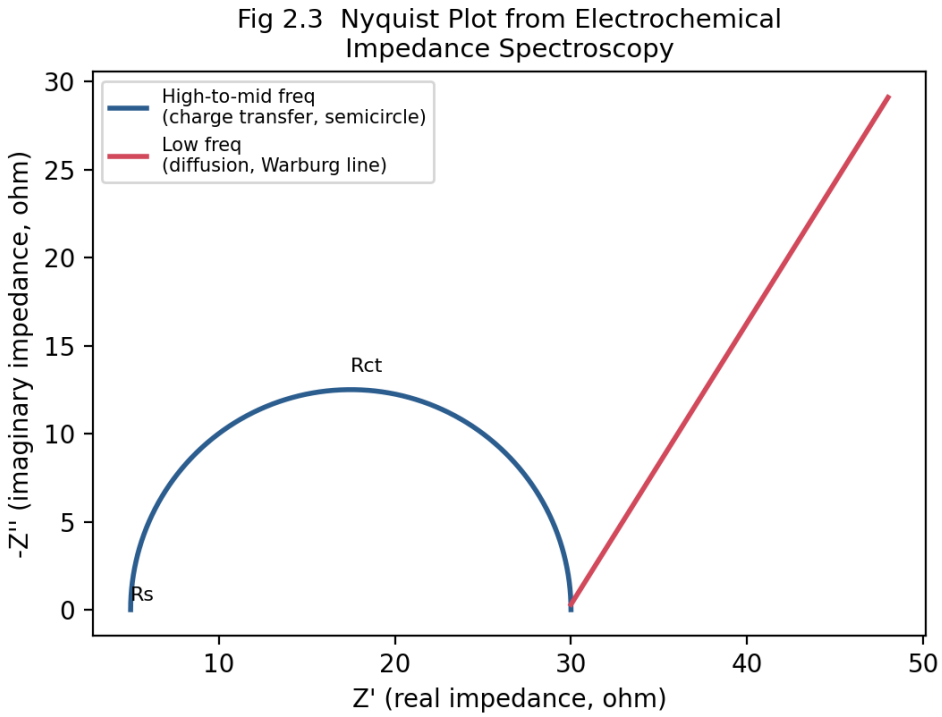

Fig 2.3 – Typical Nyquist plot: high-frequency semicircle (charge transfer, Rct) followed by a low-frequency Warburg line (diffusion).

4. Electrochemical Stability

- **Degradation mechanisms:** over-oxidation of the polymer backbone, irreversible side reactions with the electrolyte, loss of conjugation, and mechanical fatigue/cracking during repeated volume change.
- **Cycling stability:** capacity/charge retention measured over many repeated redox (charge/discharge or actuation) cycles; conducting polymers typically show more capacity fade than inorganic battery materials because of their softer, swelling-prone structure.
- **Self-discharge:** gradual loss of stored charge/potential on open circuit, arising from slow internal redox shuttling, side reactions or ionic leakage.
- **Factors affecting performance:** electrolyte choice and ion size, film thickness and morphology, operating potential window, temperature, and mechanical constraint (e.g. supporting substrate) all influence rate capability, stability and achievable strain/charge capacity.

Quick recap: EAP electrochemistry rests on Faradaic charge transfer overlaid on double-layer (non-Faradaic) charging; Butler–Volmer/Tafel kinetics describe the rate of electron transfer, while CV, chronoamperometry/potentiometry and EIS are the standard tools used to extract redox behaviour, capacity and resistance/diffusion parameters, all of which ultimately govern device stability and performance.

UNIT III – Electroactive Polymer Devices

Contact hours: 12

1. Electrochemical Actuators

EAP actuators convert electrical/electrochemical energy directly into mechanical motion, typically through ion insertion/expulsion that swells or contracts the polymer. Because they operate at low voltage, are lightweight and flexible, they are often called **artificial muscles**.

- **Linear actuators:** a free-standing polymer film or fibre contracts/expands along its length when switched between oxidised and reduced states, generating a push/pull force.
- **Bending actuators:** built from layers with different (or opposing) volume-change behaviour; when one layer expands and the other does not (or contracts), the composite bends – this is the most common EAP actuator architecture because it produces large, visible displacement from small strain.
- **Bilayer and trilayer actuators:** a bilayer pairs one active polymer layer with a passive/counter layer; a trilayer sandwiches an ion-storage/electrolyte layer between two active polymer electrode layers, allowing both layers to work antagonistically (one expands while the other contracts) for greater bending.
- **Fibre and textile actuators:** conducting polymer coated or spun into fibres/yarns that can be woven into textiles, enabling actuating fabrics, smart sutures and wearable haptic devices.

Fig 3.1 Bilayer Electrochemical Bending Actuator

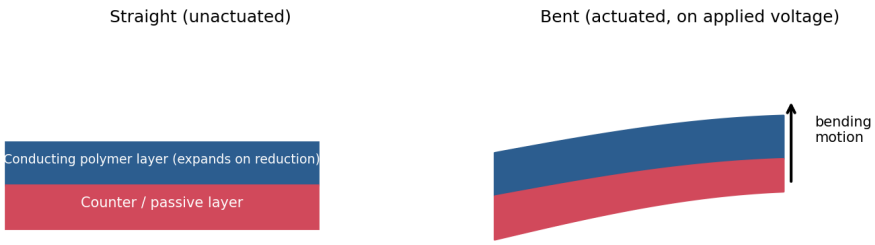

Fig 3.1 – A bilayer actuator: differential expansion of the active (blue) layer relative to the passive/counter (red) layer produces bending when a voltage is applied.

2. Sensors

The same electro-chemo-mechanical coupling that drives actuation can run in reverse: mechanical deformation of an EAP generates a measurable electrical signal, or a chemical/biological binding event changes the polymer's electrical properties. This makes EAPs naturally suited to sensing.

Fig 3.2 Major Classes of Electroactive Polymer Sensors

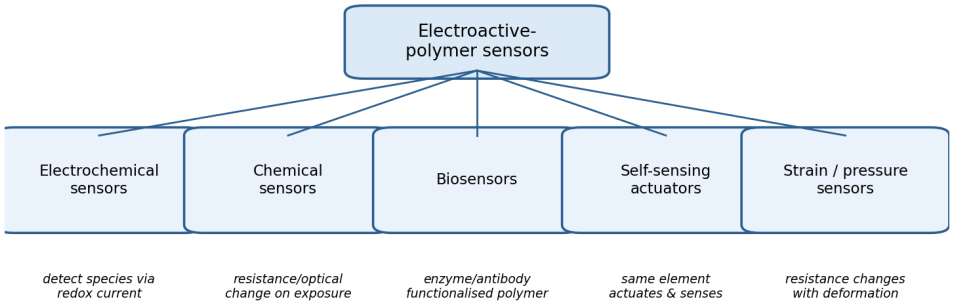

Fig 3.2 – Major categories of EAP-based sensors and their typical sensing mechanism.

- **Electrochemical sensors** – detect an analyte from the Faradaic current it produces or modulates at the polymer electrode.
- **Chemical sensors** – exposure to a target gas/vapour changes the polymer's resistance, colour or swelling, which is measured as the signal.
- **Biosensors** – the conducting polymer is functionalised with an enzyme, antibody or DNA probe; selective binding changes the electrochemical or electrical response, giving high specificity.
- **Self-sensing actuators** – a single EAP element is used simultaneously as actuator and sensor, since its own electrical response (e.g. back-EMF or resistance change) tracks its deformation, removing the need for a separate position sensor.
- **Strain and pressure sensors** – deformation directly changes the film's resistance or capacitance, enabling flexible/wearable strain and pressure sensing.

3. Device Fabrication Methods

- **Thin films** – deposited by electropolymerisation, spin-coating, drop-casting or spray coating for planar devices and coatings.
- **Nano- and micro-fibres** – produced to increase surface area and mechanical flexibility for actuators, sensors and tissue scaffolds.
- **Electrospinning** – a high voltage is applied between a polymer-solution-filled needle and a grounded collector; the resulting charged jet undergoes a whipping instability that thins and solidifies it into continuous nanofibres collected as a non-woven mat.
- **Hydrogels** – water-swollen, cross-linked polymer networks that combine ionic conductivity with tissue-like softness, useful in bioelectronics and drug-delivery devices.
- **Composite electrodes** – EAPs combined with carbon nanomaterials, metal nanoparticles or other polymers to improve conductivity, mechanical strength or cycling stability.
- **3D printing** – additive manufacturing (e.g. direct-ink-writing) of EAP-containing inks allows complex, custom device geometries not accessible by film casting.
- **Flexible electronics** – EAPs are printed or laminated on flexible/stretchable substrates for wearable and conformable devices.

Fig 3.3 Electrospinning Set-up for Nano/Micro Fibre EAP Devices

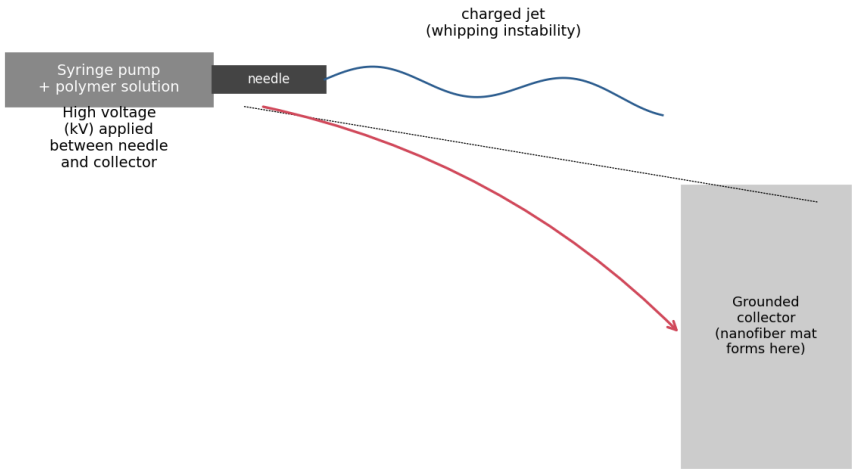

Fig 3.3 – Basic electrospinning set-up used to fabricate EAP nanofibre mats.

4. Performance Characterization of EAP Devices

- **Actuation performance:** usually reported as strain (%) and stress/force generated under a given applied voltage or current.
- **Force generation:** the blocked (maximum, zero-displacement) force an actuator can exert, often normalised by cross-sectional area to give stress.
- **Response time:** the time taken to reach a defined fraction of full displacement/force after the stimulus is applied; depends strongly on ion diffusion rate within the film.
- **Efficiency:** ratio of useful mechanical work output to electrical energy input; typically modest for EAPs compared with piezoelectric or electromagnetic actuators, but compensated by low voltage operation and softness.
- **Durability:** number of actuation cycles the device can sustain before significant performance loss, closely linked to the electrochemical stability topics covered in Unit II.

Quick recap: EAP devices exploit the same electro-chemo-mechanical coupling in two directions – as bending/linear actuators (artificial muscles) when driven electrically, and as electrochemical/chemical/bio/strain sensors when responding to an external stimulus; fabrication methods from thin-film casting to electrospinning and 3D printing shape the final device, whose quality is judged by strain, force, response time, efficiency and cycling durability.

UNIT IV – Emerging Applications and Future Directions

Contact hours: 9

1. Energy Applications

Conducting and other electroactive polymers store charge through fast, reversible surface or near-surface redox reactions (often called pseudocapacitance) in addition to any electrical double-layer charging, giving them higher capacitance than purely double-layer (carbon) electrodes while retaining reasonably fast charge/discharge.

Fig 4.1 Electroactive-Polymer Based Supercapacitor (schematic)

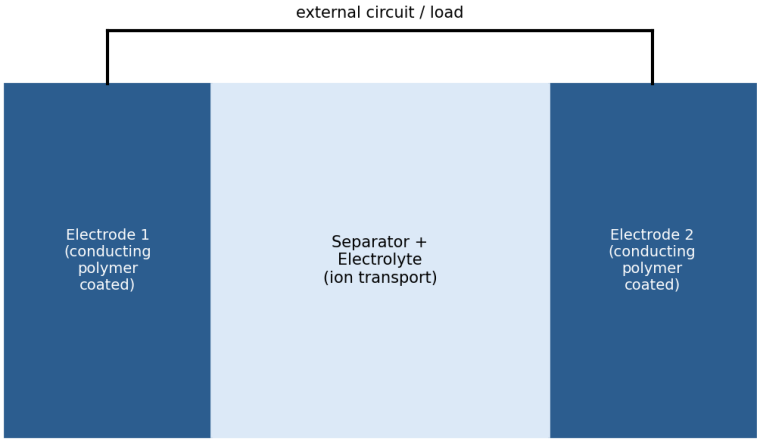

Fig 4.1 – Schematic of an EAP-based supercapacitor: two polymer-coated electrodes separated by an ion-conducting electrolyte/separator.

- **Supercapacitors:** conducting-polymer electrodes (PANI, PPy, PEDOT) give pseudocapacitive charge storage with higher energy density than carbon-based double-layer capacitors, while retaining much of their fast charge/discharge and long cycle life when properly stabilised.
- **Rechargeable batteries:** conducting polymers act as active electrode materials, conductive additives/binders, or protective coatings (e.g. on lithium or sulfur electrodes) that also help suppress unwanted side reactions.
- **Hybrid energy storage:** combining a battery-type electrode with a capacitor-type (EAP) electrode in one cell aims to capture both high energy density and high power density.
- **Flexible energy devices:** the mechanical softness of EAPs allows batteries and supercapacitors to be built directly onto flexible or stretchable substrates for wearable electronics.

2. Biomedical Applications

- **Drug delivery:** redox switching of the polymer changes its volume or charge, allowing electrically triggered, on-demand release of a loaded drug from the film.
- **Tissue engineering:** conducting polymer scaffolds provide both mechanical support and electrical cues that can promote growth of electrically excitable tissue such as nerve or cardiac muscle.

- **Neural interfaces:** conducting polymer coatings on metal microelectrodes lower electrode impedance and improve charge-injection capacity, improving the quality and biocompatibility of recording/stimulating neural signals.
- **Artificial muscles:** EAP actuators are explored for prosthetics, implantable pumps and assistive devices where soft, low-voltage, muscle-like actuation is preferred over rigid motors.

3. Soft Robotics

- **Biomimetic systems:** EAP actuators are used to build robotic fish, crawling or gripping soft robots that mimic the smooth, continuous motion of biological muscle rather than rigid joints.
- **Wearable electronics:** flexible EAP-based sensors and actuators integrated into clothing or accessories for health monitoring, haptic feedback or assistive motion.
- **Smart textiles:** EAP-coated or EAP-spun fibres woven into fabric to give the fabric itself sensing or actuating capability.
- **Human–machine interfaces:** EAP-based tactile sensors and haptic actuators that let a machine both sense human touch/motion and give the user physical feedback.

Fig 4.2 Biomedical and Soft-Robotics Applications of EAPs

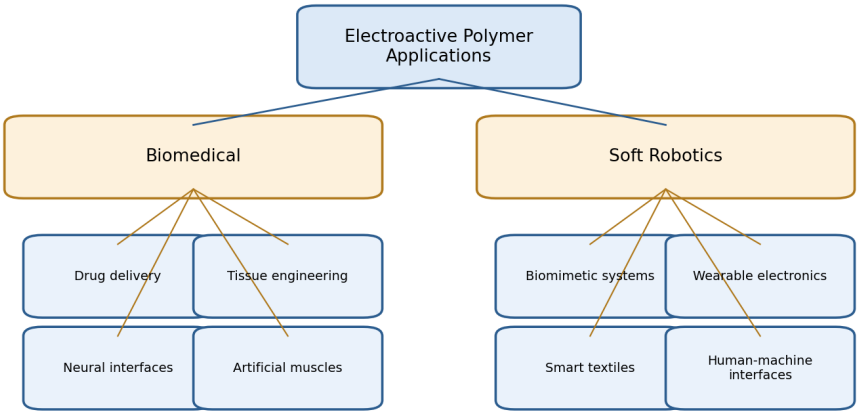

Fig 4.2 – Overview of biomedical and soft-robotics application areas for EAPs.

4. Emerging Trends and Future Directions

- **AI-assisted materials discovery:** machine-learning models trained on existing structure–property data are increasingly used to screen candidate monomers/dopants and predict conductivity, stability or actuation strain before synthesis, shortening development cycles.
- **Multifunctional polymers:** single materials engineered to simultaneously sense, actuate and store energy, reducing device complexity.
- **Sustainable electroactive polymers:** interest in bio-derived monomers, greener doping/synthesis routes and recyclable or biodegradable EAPs to reduce the environmental footprint of devices.
- **Future challenges:** improving long-term electrochemical/mechanical stability, achieving higher energy efficiency, scaling up reproducible fabrication, and standardising testing protocols so devices from different labs can be fairly compared.
- **Commercialization:** translating promising lab-scale EAP devices into manufacturable, cost-effective products requires addressing cycle life, batch-to-batch reproducibility and integration with existing electronics manufacturing.

Quick recap: the pseudocapacitive, redox-tunable nature of EAPs is being pushed toward energy storage (supercapacitors, batteries), biomedical devices (drug delivery, neural interfaces, artificial muscles) and soft robotics/wearables, with AI-guided design and sustainability now shaping the next generation of these

materials and their path to commercial devices.