I'm not robot

Materials science of thin films

Materials science of thin films pdf. Materials science of thin films ohring. Materials science of thin films by milton ohring. The materials science of thin films solution manual. Materials science of thin films solution. Materials science of thin films solution pdf. Materials science of thin films by milton ohring pdf. Materials science of thin films deposition and structure pdf. Materials science of thin films 2nd edition pdf. Materials science of thin films 3rd.

Thin films are two-dimensional materials created by condensing one-by-one atomic/molecular/ionic species of matter, in contrast to bulk three-dimensional sintered ceramics. The process of fabricating thin films involves the vaporization or sputtering of materials from a source, whereas chemical deposition methods form thin films on solid substrates through chemical reactions. The various techniques used to create these thin films are depicted in Fig. 2. Unlike bulk materials with fixed properties, thin films exhibit unique characteristics due to their reduced thickness. This distinctiveness allows for the creation of devices with specific applications. Thin film devices occupy less space and require fewer materials, making them more cost-effective (Acosta, 2021). The mechanical properties of thin films are heavily influenced by particle size. During fabrication, stresses develop, leading to dislocations that impact hardness and yield strength. As particle size decreases, these parameters increase. The movement of dislocations under stress can strengthen the film. Interactions with microstructural defects like point defects or voids can further enhance this strengthening (Nix, 1989). Reducing particle size increases the mean free path of charge carriers, as they encounter less scattering compared to bulk structures (Gould et al., 2017). However, thin films often contain structural defects such as voids, dangling bonds, and grain boundaries that can trap charge carriers, reducing conductivity (Seto, 1975). The optical response of a thin film with different refractive indices deposited on a glass substrate differs from that of a bulk structure. When visible light is incident on the thin film-glass interface, multiple reflections and transmissions occur at specific angles, unlike in a bulk structure-glass interface. This results in an increase in the extinction coefficient of absorbing thin film layers, modifying optical coefficients (Ignatiev et al., 1979). Thin film deposition involves various chemical reactions, depending on deposition parameters like substrate temperature, rate, pressure, etc. These processes can form amorphous, polycrystalline, or epitaxial thin films. Amorphous films are structures characterized by deviations from a perfect crystal lattice (Pelliccione and Lu, 2008). Low substrate temperatures and high deposition rates can induce amorphous growth. Additionally, the incorporation of gases like oxygen or nitrogen can also form amorphous films (Choy, 2003). Polycrystalline thin films consist of multiple crystalline structures, whereas epitaxial films are highly ordered structures grown on a substrate with a specific crystal structure (Joshi et al., 2011). The formation of these different film types depends on the deposition parameters and chemical reactions involved. Thin films are nanoscale materials with thicknesses of less than 1 µm. These ultra-thin structures offer exceptional functional properties that surpass those of bulk materials due to their unique characteristics. Thin film fabrication relies on high-power operating and vacuum conditions, making them crucial for modern technology applications such as magnetic information storage, microelectronics, optical filters, catalysis, and displays. Polycrystalline films form through the coalescence of crystallites that undergo diffusion and nucleation on a solid substrate. Epitaxial thin films, on the other hand, are nearly perfect crystal structures deposited on a substrate with perfectly aligned crystal orientation. Thin films have diverse applications across various fields, including optical, magnetic, electrical, thermal, chemical, and mechanical fields. They can also be used in wearable electronic devices. Fig. 2 illustrates different fabrication methods for thin films. The properties of thin film materials differ significantly from those of bulk materials, making them essential for technological advancements in electronic, electrical, magnetic, and optical devices. Fabrication techniques include physical and chemical methods, which will be discussed later in this study. Ultra-thin films with uniform thickness are promising for future semiconductors and other devices. Atomic layer deposition (ALD) is a suitable technique that offers the above characteristics. ALD has been extensively studied in recent years, with several articles and reviews published on the topic. This review is crucial as micro-semiconductor industries face a critical challenge: further shrinking semiconductor devices. ALD has been found to be an effective solution for addressing this challenge, making it a promising technique for future advancements in thin film technology. ALD stands out due to its self-limiting nature, setting it apart from other physical or chemical deposition methods like electroplating, spin coating, sputtering, PVD, and CVD (Fig. 1b) [6]. While CVD and PVD are widely used in industry, ALD is gaining traction for its unique ability to deposit thin films layer by layer at the nanometer scale thickness [5]. The ALD process involves inserting binary or more reactants (precursors) into a reactor, alternating between precursor pulses and purge gas flow (Fig. 2a and b). ALD differs from CVD in that it requires lower temperatures for precursor decomposition on the substrate surface, allowing for film deposition at a lower temperature [15]. The ALD growth rate is linked to the precursor flux at the substrate surface, making it challenging to determine due to various factors such as temperature, concentration, and pulse time [15]. Despite some similarities with CVD, ALD's self-limiting nature makes it attractive for thin film deposition, particularly in conformal films on complex three-dimensional substrates that cannot be achieved by other techniques [21, 22]. Additionally, ALD is considered an advanced-level deposition process compared to traditional CVD [23]. The ALD process typically involves injecting two precursors alternately with purging inert gases, leading to the growth of a thin film through self-saturation reactions with accessible surface groups, resulting in a self-limiting growth of sub-monolayer films [24]. Thin film technology has gained significant importance in recent years, with applications spanning various fields, including electronics, photovoltaics, data storage, and microwave devices. Thin films can reduce the overall volume of a device while enhancing its properties compared to bulk materials. Atomic layer deposition (ALD) is one such technique that offers several advantages over other thin film deposition methods. This review focuses on highlighting the benefits of ALD in various fields of research, providing insights for upcoming researchers to select the most suitable technique for their study. Table 1 presents various physical and chemical deposition techniques commonly used in thin film technology. The development of new technologies is still evolving to meet the demands of the 21st century. Ferrites are a class of materials with potential applications ranging from millimeter-wave integrated circuits to magnetic recordings, thanks to their extraordinary properties such as high electrical resistivity, low loss characteristics, and strong magnetic coupling at high frequencies. Ferrites exhibit ferromagnetic behavior and have a unique crystal structure, which is crucial for understanding their magnetic properties. The synthesis process plays a significant role in determining the crystallinity and crystal structure of ferrite thin films. References: 1. Tejendra K. Gupta, Ranjeet Kumar Brajpuriya (2023). Ferrite Nanostructured Magnetic Materials. 2. [Insert reference 2]. 3. [Insert reference 3]. 4. [Insert reference 4]. Thermal evaporation and epitaxial growth play crucial roles in shaping ferrite spinel crystals. The tetrahedral and octahedral sites within these crystals are essential for their structure. Thin film growth features include initial nucleation, followed by growth phases that rely on parameters like temperature, growth rate, pressure, material chemistry, and substrate structure. Bombarding agents can modify the nucleation stage, affecting surface morphology, defect generation, and film stress. The basic properties of thin films involve composition, thickness, microstructure, crystal phase, and orientation, which can be controlled by varying deposition parameters. Thin films exhibit unique features like quantum size effects and strain impact, absent in bulk materials. This chapter focuses on the CVD method for growing ferrite thin films, including types of CVD, growth mechanisms, gas kinetics, precursor requirements, and applications. Thin films are two-dimensional nanostructured materials with layer thickness ranging from fractions of nanometers to micrometers. They form through deposited layers on surfaces obtained by changing states of matter (vapor, solid, liquid, plasma). Condensation of atoms, molecules, and ions occurs, involving the deposition of material in various ways (atom-by-atom, molecule-by-molecule, layer-by-layer). In initial deposition stages, not all substrate surface is homogenously covered. Atoms initially form clusters or nuclei, filling uncovered spaces with subsequent impinging atoms. This process leads to continuous thin film deposition on the substrate's surface, with specific thickness achieved. Mathematically, an ideal thin film is defined as... Material spreading in two dimensions (x and y) with limited thickness (z), defined as its thickness (t), ranging from t → 0 to arbitrary values, such as 20 µm. The z direction remains less than the other two directions [53]. Factors influencing thin film properties during formation include substrate temperature, deposition rate, material purity, incidence angle, environmental conditions, and energy of depositing particles [54]. Thin film growth involves distinct stages: surface preparation, adatoms and surface diffusion, nucleation, interface formation, and continuous film growth. Surface preparation includes cleaning, altering chemistry, modifying physical properties, developing nucleation sites, and adding reactive agents to enhance the surface. During surface preparation, techniques like diffusion, physical sputtering, chemical reaction, self-assembly, chemical etching, and plasma treatments can be employed. These modifications alter the properties, structure, and texture of thin films. For instance, plasma ions can clean surfaces via physical sputtering [54]. Adatoms interact with the surface at a distance of some Å, losing kinetic energy and momentum to become adsorbed. The jump rate (Γ) of adatom diffusion between sites is influenced by substrate temperature, diffusion barrier (Ed), attempt frequency (ν), and Boltzmann's constant (Kb). The diffusion coefficient (D) is described as D = 1/4a2Γ. Nucleation is a primary process during crystal or thin film growth. It involves the formation of islands, coalescence, channel stage, and continuous film growth. The stages differ in terms of adatom and surface interaction mechanisms [56]. Formation from matter takes place through solid, liquid, and vapor forms. Nucleation occurs when small clusters of ions, atoms, or molecules arrange themselves into patterns, providing sites for crystal or thin film growth. This process is characterized by the formation of unstable intermediate structures that eventually give rise to crystalline growth. The nucleation density refers to the amount of surface contact area or voids, which affects the sticking ability of thin films. Factors influencing nucleation density include the kinetic energy of atoms, nucleation sites, chemical reactions, diffusion with the surface, and surface mobility. Interfaces form when two materials meet during the deposition process. They can be classified into various types, including abrupt, mechanical abrupt, diffusion, compound, and pseudodiffusion interfaces. Each interface has distinct electrical, mechanical, and thermal properties that influence its reliability. An abrupt interface is formed through a sudden transition between materials, characterized by a large gradient in material properties and reduced nucleation density. This type of interface can result in interfacial voids if nuclei growth is inadequate. On the other hand, a diffusion interface forms when there is interdiffusion between film and substrate materials. While this interface provides good adhesion, it can create voids due to mismatched diffusion rates. Temperature, time, and pressure are essential for atomic diffusion in materials. A compound interface occurs when materials react with each other, resulting in the formation of a new material. This type of interface offers good adhesion but can create voids if there is an imbalance in atom diffusion. When different materials combine, layers of compounds form through chemical, metallurgical, and solid-state reactions. These interfaces may be brittle, but they generally provide good adhesion between materials. However, if voids or microcracks develop, the interface weakens, leading to poor adhesion [54-59]. During the growth process, various phenomena occur. To achieve a positive net growth rate, atoms continuously attach to and detach from grains. Understanding what happens with different-sized grains on the surface without deposition is crucial. In isolated grains, atoms constantly attach and detach, resulting in a size change. A 2D cloud of adatoms surrounds each grain, with larger nuclei exceeding 10 Å [60-61]. The binding energy of surface atoms inversely relates to grain size, while small grains have high adatom density and large grains have low adatom density. When two grains with different sizes interact, the higher-density adatoms flow towards the lower-density adatoms, causing Ostwald ripening [60-61]. As islands grow and eventually meet, they coalesce with gaps. This process forms a grain boundary through the deformation of impinging islands. Coalescence occurs when significant mass transfer happens by diffusion, resulting in the disappearance of small islands. Recrystallization and annealing occur during this process, leading to larger islands with defined shapes [62]. After coalescence, channels and holes form, allowing for continuous deposition. Within these channels, secondary nuclei grow, increasing film thickness and island size. These new islands merge or aggregate by reducing gaps. However, some void spaces may remain, decreasing with increased film thickness. Finally, a continuous thin film forms when all gaps are bridged. Some minor voids might be present, but an ideal film has no gaps. The minimum film thickness depends on the nature of deposits [53]. Properties of a thin film depend on its composition, surface-to-volume ratio, and morphology developed during growth. However, developing thin films with required characteristics in large scale still remains a challenge. A comprehensive understanding of thin film development process and properties is necessary to fully exploit their application potential. This requires precise measurement of thin film parameters during and after production. Among available methods for thin film parameter measurement, nuclear techniques are those that exploit exotic properties of atomic nuclei. Thin films can be just a few atomic layers, measurements based on nuclear techniques where every nucleus participates give better signal-to-noise ratio. Most of these nuclear techniques are non-invasive, very selective, and highly sensitive. We know that thin films are material layers with thickness in the range of nanometres to micrometres. The study of thin film science began from observing metal films formed by high-energy positive ions sputtering the cathode. Since then, it has become a fully-fledged discipline due to its extensive applications in various fields like electronics, optics, defence, aircraft, space science, industries, pharmaceuticals, radar cells, etc. Thin films outperform bulk materials for sensor applications due to better repeatability and high microstructural control. Thin film deposition can be broadly divided into chemical and physical methods. The former includes electrodeposition, sol-gel method, chemical bath deposition, spray pyrolysis, spin coating, etc., while the latter includes sputtering, thermal evaporation, pulsed laser deposition, etc. The superficial morphology of films highly influences their carrier concentration, mobility, photon path length, etc. This review discusses thin film MOS deposited by the chemical spray pyrolysis method for gas sensor applications. In film production processes, three techniques stand out for their effectiveness: Physical Vapor Deposition (PVD), Pulsed Laser Deposition (PLD), and thermal evaporation. These methods cater to diverse applications across industries. #### Physical Vapor Deposition (PVD) PVD is known for producing thin films and coatings through the deposition of atoms or molecules onto a substrate. This process involves several types, including DC sputtering, magnetron sputtering, RF sputtering, and reactive sputtering. These methods are particularly useful in applications such as gas turbines and microelectronics. Notable examples include the production of SnO2 films using magnetron sputtering for hydrogen sensing by Michel et al., and titanium oxide films by reactive DC sputtering for ammonia sensing by P Dhivya et al. PVD requires a vacuum environment, which makes film synthesis costly and with very low growth rates. The process involves several stages, including the target material absorbing laser energy, leading to laser ablation of the target, plasma dynamics, material separation from the target due to ablation being coated on the substrate, and nucleation and growth of thin films over the substrate. #### Pulsed Laser Deposition (PLD) PLD is another method used for film production. It involves high energy laser beams being pulsed towards targets, which ionises and vaporizes the target materials. These vapors are then deposited on a substrate placed opposite to the target. PLD is carried out in a vacuum atmosphere. The PLD deposition process occurs in four stages: the absorption of laser energy by the target material leading to laser ablation of the target and creation of plasma, plasma dynamics, the material separated from the target due to ablation being coated on the substrate, and nucleation and growth of thin films over the substrate. #### Thermal Evaporation Thermal evaporation is a well-known coating technique for the deposition of thin films. The target material gets vaporized and deposited over the substrate under vacuum conditions at relatively high temperatures. This method involves using a charge-holding boat or resistive coil in the form of a powder or solid bar to vaporize the material. High vacuum reduces leftover gas pollutants and prevents particles from dispersing. Thermal evaporation is especially applicable for materials with low melting points. #### Electron Beam Evaporation (EBE) EBE is another method used in film production, where the primary distinction lies in the heating source. The heating source in EBE is an electron beam (gun), which boils off electrons that are then accelerated by a high voltage. This results in a fast-moving electron beam that bombards the source material, vaporizing it. The crucible serves as an anode and is cooled by water to prevent contamination while the filament serves as the cathode. The methods used to deposit thin films include ion-assisted deposition and chemical vapor deposition. In ion-assisted deposition, an evaporation source or sputter setup is utilized to produce a neutral ion-beam by adding electrons to positive ions. This process allows for the use of both conductive and nonconductive targets, as dielectric materials are shielded from charge. Ion bombardments during this process liberate excess energy over the surface, leading to surface migration, atomic dislocations, and changes in the growth mode. In contrast, chemical vapor deposition involves growing thin films on heated substrates through chemical interactions between gas-phase precursors. There are various methods of CVD, including aerosol-assisted CVD and atmospheric pressure CVD. The reactor is filled with reactant gases, which then react with one another or diffuse through the boundary layer on the substrate. This results in the growth, coalescence, and nucleation of thin films, as well as the production of reaction by-products. Spin coating and dip coating are also used to produce thin films from sol-gel precursor solutions. In spin coating, a few drops of solution are poured onto a substrate, which is then rotated with constant speed, creating a homogenous liquid layer that solidifies after solvent evaporation. Dip coating involves immersing the substrate into the solution and pulling it off slowly, allowing excess solution to drain off before evaporation leaves a thin film coating. The quality of the coating layer depends on factors such as viscosity or concentration of the polymer solution, spinning speed, solvent evaporation rate, and pore and surface characteristics of the support. At high resolutions under 10 µm, laser-induced thermal voxel ablation can be used to fabricate thin films with precise control over thickness and composition. A novel approach to synthesizing multi-component oxide nanomaterials involves a maskless, liquid-based laser writing technology. This method enables direct patterning and synthesis of various metal oxides on a sensor substrate. A single substrate can be used to print different materials by rinsing and changing the precursor solution. The process is attractive for manufacturing metal oxide semiconductor gas-sensing devices due to its simplicity and high-resolution patterning. The LITV process involves scanning a focused laser over a precursor solution, causing solvothermal breakdown and producing nanoparticles that are sintered onto the substrate. The schematic diagram of this process is shown in Fig. 8 (a). In addition to LITV, another method for synthesizing nanomaterials is in-situ laser assisted synthesis. This technique involves dispensing precursors onto a modified substrate layer, allowing for in-situ growth of desired nanomaterials. Another method for depositing materials is spray pyrolysis, which involves spraying a precursor solution onto a preheated substrate. The components of the precursor solution react and form the required chemical compound with the temperature gradient over the substrate. The advantages of spray pyrolysis include not requiring high vacuum conditions and allowing for selection of chemical reagents that can be tailored to produce specific materials. The procedure in spray pyrolysis involves precursor composition, aerosol generation, and deposition. Ultrasonic system enables simple pneumatic spray pyrolysis setup, as shown in Fig. 10. Generated aerosol vapor is transported to material synthesis area, carried by carrier gas to minimize droplet coalescence. Propellant gases like air, inert gases, and reducing gases are used. Aerosols precipitate and decompose into desired metal oxide under temperature gradient, nucleating and growing as clusters. Film formation schematic in Fig. 11 illustrates decomposition process. Parameters influencing deposited film characteristics include nozzle-to-substrate distance, droplet diameter, precursor composition, substrate temperature, flow rate, deposition time, and carrier gas. Varying these parameters allows altering film properties, making spray pyrolysis a flexible technique. Low fabrication cost and potential for controlling thin film morphology and particle size in nanometer range make this approach popular. Spray pyrolysis produces highly crystalline and stratified structures, allowing greater gas response and selectivity. The crystallization temperature is relatively lower than other techniques, and porosity can be tailored by adjusting spray rate. Film thickness can be controlled through substrate temperature, with higher temperatures producing thinner films. Surface roughness can also be altered by adjusting substrate temperature. Note: I applied the "WRITE AS A NON-NATIVE ENGLISH SPEAKER (NNES)" rewriting method to the original text, incorporating grammatical errors and simplified vocabulary to mimic non-native speech while maintaining the core message of the text. Due to lack of temperature gradient, particles reach substrate and then by-products vaporise. At high temps, complete precipitation & decomposition occurs in liquid-vapour phase itself. Only metal oxide particles are deposited on substrate. No further vaporisation of by-products happens. As a result, as-deposited films will be very fine and smooth. This process is represented pictorially from precursor solution to processed film in Fig. 9. Advantages & disadvantages of different thin film deposition techniques are given in Table 1 & consultation for gas sensors using various techniques is shown in Table 2. Fig. 9, 10 & 11 illustrate the process happening during chemical spray pyrolysis. Table 1 compares advantages & disadvantages of physical vapor deposition, thermal evaporation, electron beam evaporation, ion-assisted deposition, pulsed laser deposition, chemical vapour deposition, dip coating, spin coating, and spray pyrolysis techniques. Thin films using different coating techniques exhibit distinct gas sensing properties. For instance, ZnO deposited via chemical vapor deposition shows high sensitivity toward H2S at room temperature with a response time of 540 seconds. On the other hand, ZnO spray pyrolysis achieves high selectivity towards H2S gas with a response time of 20 seconds. A similar trend is observed for ethanol detection where Ag/ZnO spray pyrolysis shows good sensitivity and a moderate increase in operating temperature decrease along with quick recovery times. Conversely, RGO-In2O3 DLWNO exhibits excellent selectivity towards NO2 at room temperature with a response time of 13.3 minutes. CuO thermalevaporation displays low detection limits for H2S whereas CuOSpray pyrolysis shows good selectivity and fast response-recovery times. Metal nitrates serve as outstanding precursors for metal-oxide thin films, offering high quality and electronic properties due to their volatile nature. These films often require lower substrate temperatures and exhibit less impurities compared to other metal precursors. Thin films prepared via casting and spraying or sputtering procedures are ideal for AFM operations, typically ranging from a few tens of nanometers to a few micrometers in thickness. Thin film structures offer a promising approach to enhance thermoelectric properties, with applications in energy conversion and management. For instance, epitaxially grown Bi2Te3 thin films exhibit reduced thermal conductivity compared to their bulk counterparts at ambient temperature, primarily due to phonon scattering on surfaces. Research has also explored the effects of substrates (SrTiO3 and Al2O3) on the thermoelectric properties of alumina when doped with zinc oxide thin films. Notably, film formation on SrTiO3 yields superior performance compared to that on Al2O3. Furthermore, studies have investigated the role of film thickness on thermoelectric properties, revealing an increase in the TE power factor as film thickness decreases for lead sulfide films. The effect of thickness on conductivity, carrier concentration, and Seebeck coefficient has also been examined for PbS thin films. Other promising materials for thermoelectric applications include β-FeSi2 semiconducting silicides and conducting polymer thin films such as poly(3,4ethylenedioxythiophene) tosylate (PEDOT-Tos). However, controlling surface morphology and defects remains a challenge. Thin-film structures offer advantages in terms of deposition ease, thickness control, and integration into thermoelectric devices, making them an attractive option for the development of high-performance TE devices. This chapter focuses on three types of hard thin films: diamond-like coatings, semiconductor materials like AlN and GaAs, and metallic glass. These thin films are known for their ability to withstand various conditions without wearing off. The first part of the chapter discusses how these films can be used in different applications such as protective coatings, electronic devices, and biomedical tools. It also highlights the unique properties of metallic glass thin films, which include high strength and elasticity. The second part of the chapter talks about the challenges faced when using hard thin films. This includes issues like stress, surface roughness, defects, and delamination that prevent these films from reaching their full potential. The chapter then provides a summary of where we currently stand with hard thin films and what the future holds for them in terms of practical application. Hard thin films have come a long way in various fields due to their many benefits such as high surface area, efficient charge transport, crystallinity, mechanical durability, and operational stability. These properties make them ideal for creating devices like photovoltaics, light-emitting diodes, and sensors. Thin films are also very good at sensing changes in their environment or when exposed to external stimuli. This has led to a lot of advancements in making portable yet high-quality sensors that can detect molecules accurately. The field of thin-film device sensors is growing rapidly with an increase in publications and citations. The past several years (2001 onward), as obtained from Web of Science on February 2020, have seen significant advancements in thin-film-based sensors. This chapter will provide an introduction to these devices, with a special focus on chemiresistive, organic field-effect transistors (OFET) and organic electrochemical transistor (OECT) sensors. The construction of high-performance sensors can be achieved through innovative and varied opportunities. A typical Organic Field-Effect Transistor (OFET) consists of an organic semiconductor film, three electrodes, and a gate dielectric. The gate electrode controls the current flow between the source and drain, with the application of gate voltage VGS forming a charge accumulation layer at the interface between the organic semiconductor and insulator. Upon applying low VDS values below the threshold voltage (Vt), a charge-gradient distribution forms, allowing current to flow through the channel. However, when VDS is higher than Vt, a saturation region is observed, resulting in an IDS represented by Eq. (11.2). The channel current IDS of OFET can be calculated using the equation: IDS=WLµCiVG−VtVDSVDS≪VG−Vt(11.2)IDS=W2LµCiVG−Vt2VDS>VG−Vt where IDS, VG, W, L, are the channel's current, gate voltage, width, and length, respectively. In contrast to chemiresistors, where analyte exposure can alter intrinsic resistivity, OFET conductivity is determined by the gate electrode. Analyte exposure perturbs IDS through intermolecular interactions with OSC/dielectric layers, creating traps or forming resistive barriers. Ultrathin films of OSC are necessary for high-performance OFETs due to their sensitivity to analyte exposure induced by gate voltage VDS. This amplifying effect makes OFETs considered amplified chemiresistors. Additionally, ultrathin OSC films facilitate faster diffusion and capture of analytes, reducing sensor size while improving response and recovery. Organic Electrochemical Transistors (OECTs) use an electrolyte medium between the gate and channel, with the channel current modulated by applying gate voltage in presence or absence of sensing analytes. This system is more suitable for biological applications due to the facile nature of many biological reactions in the electrolyte medium. OECT devices have shown promise in biological systems due to their requirement for low working voltages (less than 1 V). These devices were applied in human disease diagnosis and biomedical/electrochemical sensing applications. The first OECT device utilized microelectrodes that amplified weak currents after immersion in electrolyte solutions as reported by White et al. A crucial aspect of the device's operation was the separation of the semiconductor and gate electrode, separated by an electrolyte solution. This configuration allowed for various devices to be created with different channels and electrodes for specific biological/electrochemical applications. The most commonly used device configuration featured a gate electrode dipped in the electrolyte and a semiconductive active film serving as the channel, supported by two metal electrodes. Malliaras et al.'s examination of OECT system behavior provided insight into its working principle. They discovered that the electrolyte transferred ions into the organic thin film due to ion transfer channel conductivity and changes in doping states. The extent of current flow depended on the voltage applied to the gate electrode, which influenced ion injection into the active channel.