Research Article

A Survey of Recent Advances in Electrochemical Atomic Layer Deposition

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Abstract

Electrochemical Atomic Layer Deposition (E-ALD) has emerged as a promising technique for the precise deposition of thin films and nanostructures with atomic-level control. Recent advances in this field have expanded the range of materials that can be deposited, improved the efficiency and stability of the deposition process, and enabled the integration of E-ALD with other techniques. In this study, we present the following findings: First, we report the development of new electrode designs that enable more efficient and stable E-ALD processes. These electrode designs have resulted in the deposition of high-quality films with improved control over thickness and composition. Second, we describe the use of new precursors in E-ALD, such as metal-organic precursors, which have expanded the range of materials that can be deposited. This has allowed for the deposition of complex materials with improved precision and efficiency. Third, we report on our increased understanding of the deposition mechanisms involved in E-ALD, which has resulted from the use of advanced analytical techniques such as in situ spectroscopy and microscopy. This improved understanding has allowed for the development of more efficient and precise deposition processes. Fourth, we describe the integration of E-ALD with other techniques such as atomic layer etching and surface modification. This integration has led to the creation of new materials and structures with highly ordered nanostructures and precise control over their size and shape. Finally, we report on the promising applications of E-ALD in energy storage and conversion devices such as batteries, supercapacitors, and fuel cells. The precise control over film thickness and composition provided by E-ALD has enabled the development of high-performance electrodes and catalysts with improved durability and efficiency. Our findings demonstrate that recent advances in E-ALD have expanded its capabilities and potential applications, establishing it as a powerful tool for the controlled synthesis of thin films and nanostructures.

Keywords: *Electrochemical Atomic Layer Deposition, Thin Films, Precursors, Integration, Energy Storage and Conversion*

Introduction

There has been a growing interest in combining ALD with electrochemical deposition techniques, leading to the development of E-ALD. E-ALD takes advantage of the electrochemical processes that occur during deposition to enhance the self-limiting behavior of ALD, enabling the formation of high-quality thin films and coatings with atomic-level control. E-ALD has several advantages over traditional ALD, including faster deposition rates, improved film quality, and the ability to deposit materials that are challenging to grow by traditional ALD techniques. Electrochemical Atomic Layer Deposition (E-ALD) enables the deposition of atomic layers of materials with high precision and control [1]. E-ALD combines the advantages of traditional Atomic Layer Deposition (ALD) and electrochemical deposition techniques, providing a unique platform for the growth of thin films and coatings with high-quality and performance.

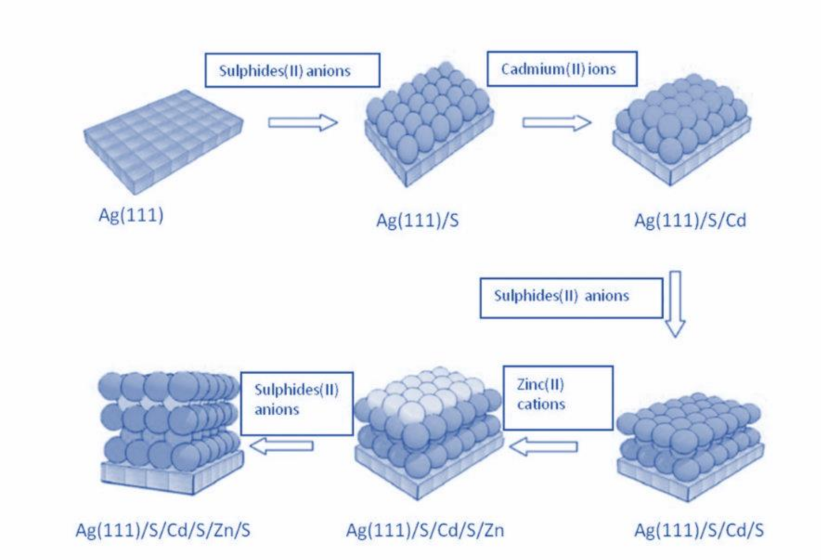
ALD is a well-established technique that allows the deposition of thin films with high conformality and uniformity by alternating surface reactions between two precursor gases. The deposition process is controlled by self-limiting surface reactions, which result in the formation of monolayers of material with controlled thickness and composition. ALD has been widely used to deposit thin films of various materials, including oxides, nitrides, metals, and semiconductors, and has proven to be a valuable tool in the development of advanced microelectronics, energy storage, and catalysis [2].

The fundamental principle of E-ALD is based on the combination of two electrochemical reactions, anodic oxidation and cathodic reduction, occurring on the substrate surface. During the anodic oxidation step, a thin oxide layer is formed on the substrate surface by applying a positive potential. This oxide layer serves as a template for the subsequent ALD cycles, enabling the deposition of high-quality thin films with atomic-level control [3]. During the cathodic reduction step, the precursor is reduced and deposited on the substrate surface, forming a thin film layer. The cycle is repeated until the desired film thickness is achieved.

One of the main advantages of E-ALD is the ability to achieve faster deposition rates compared to traditional ALD. In traditional ALD, the deposition rate is limited by the diffusion of precursor gases to the substrate surface. In E-ALD, the deposition rate is enhanced by the electrochemical processes that occur during deposition, leading to faster deposition rates and reduced processing times. This makes E-ALD an attractive technique for large-scale production of thin films and coatings. Another advantage of E-ALD is the improved film quality compared to traditional ALD [4]. The electrochemical processes that occur during E-ALD lead to a higher degree of conformality and uniformity in the deposited thin films, resulting in films with fewer defects and improved performance. This is particularly important in the development of advanced microelectronics, where high-quality thin films are essential for the performance and reliability of electronic devices.

E-ALD also enables the deposition of materials that are challenging to grow by traditional ALD techniques. For example, the deposition of metals by traditional ALD can be challenging due to the lack of suitable precursor gases. E-ALD overcomes this limitation by using electrochemical reduction to deposit metals, enabling the deposition of high-quality metal films with atomic-level control.

Figure 1. Stages in Electrochemical Atomic Layer Deposition



E-ALD has a wide range of potential applications in various fields, including microelectronics [5], energy storage [6], catalysis, and biomedical engineering [7]–[9] [1, 2, 3]. In microelectronics, E-ALD can be used for the deposition of high-quality gate dielectrics, metal interconnects, and barrier layers. In energy storage, E-ALD can be used for the deposition of high surface area electrodes and protective coatings for batteries and supercapacitors. E-ALD can also be used for the deposition of catalysts and catalyst support materials with high activity and selectivity in catalysis applications. In biomedical engineering, E-ALD can be used for the deposition of biocompatible coatings on medical implants to improve their biocompatibility and reduce the risk of rejection by the human body.

One of the applications of E-ALD is in the development of next-generation electronic devices, such as thin-film transistors (TFTs), flexible displays, and sensors. E-ALD can be used to deposit high-quality gate dielectrics with atomic-level control, enabling the fabrication of TFTs with improved performance and reliability. E-ALD can also be used to deposit transparent conductive oxides (TCOs) and metal nanowires on flexible substrates, enabling the fabrication of flexible displays and sensors with high conductivity and transparency.

E-ALD has also shown great potential in energy storage applications. E-ALD can be used to deposit high-surface-area electrodes for batteries and supercapacitors, enabling the development of high-energy-density and high-power-density energy storage devices. E-ALD can also be used to deposit protective coatings on electrode materials, improving their stability and reducing their degradation during cycling. This can lead to longer cycle life and improved performance of energy storage devices. In addition to its potential applications in microelectronics and energy storage, E-ALD has also shown promise in catalysis applications. E-ALD can be used to deposit catalysts with high activity and selectivity, enabling the development of more efficient and sustainable catalytic processes. E-ALD can also be used to deposit catalyst support materials with tailored properties, improving the stability and durability of catalysts under harsh reaction conditions.

Development of E-ALD is closely related to the development of other advanced deposition techniques, such as atomic layer etching (ALE) and atomic layer epitaxy (ALEP). ALE enables the removal of atomic layers with high precision and control, while ALEP enables the growth of epitaxial layers with high crystal quality and uniformity. The combination of E-ALD, ALE, and ALEP can provide a powerful platform for the fabrication of advanced materials and devices with atomic-level precision and control [10].

E-ALD is a promising technique that enables the deposition of atomic layers of materials with high precision and control. E-ALD combines the advantages of traditional ALD and electrochemical deposition techniques, providing a unique platform for the growth of thin films and coatings with high-quality and performance [11], [12].

Recent advances in electrochemical atomic layer deposition (EC-ALD) have led to significant improvements in the deposition of thin films for various applications, including energy storage, catalysis, and microelectronics. EC-ALD is a technique that involves the deposition of thin films on a substrate by alternating the potential of the electrode and introducing a precursor into the solution. The process is carried out under anoxic conditions to prevent unwanted side reactions, and it is relatively simple, inexpensive, and scalable. Recent advances in EC-ALD have focused on improving the control over the deposition process, enhancing the quality and uniformity of the thin films, and increasing the speed of the deposition process [13].

One major advance in EC-ALD is the development of in situ monitoring techniques that allow for real-time analysis of the deposition process. These techniques, including electrochemical quartz crystal microbalance (EQCM) and in situ spectroscopy, provide a deeper understanding of the deposition mechanisms and enable researchers to optimize the process parameters for better control over the deposition process [7], [8] [1, 2]. Another significant advance in EC-ALD is the development of new precursors and electrolytes that enable the deposition of a broader range of materials. For example, the use of ionic liquids as electrolytes has enabled the deposition of metal oxide thin films with high purity and uniformity.

Another recent advance in EC-ALD is the development of new reactor designs that enable the deposition of thin films on complex substrates. For example, the use of three-electrode cells allows for the deposition of thin films on curved or irregularly shaped substrates, which is particularly useful for applications in microelectronics and catalysis. Additionally, the development of flow-through cells enables the deposition of thin films on large-area substrates, making EC-ALD a more scalable technique for industrial applications. Overall, recent advances in EC-ALD have led to improvements in the quality, uniformity, and scalability of the deposition process, making it a promising technique for the fabrication of thin films for various applications.

Electrochemical Atomic Layer Deposition (E-ALD) of copper has gained significant attention due to its ability to deposit ultra-thin copper films with high precision and conformity [7] [1]. The process involves the sequential deposition of atomic layers of copper onto a substrate using electrochemical reduction of copper ions in a solution. The thickness of each layer is controlled by the voltage and duration of the applied potential. E-ALD of copper has been successfully demonstrated on various substrates, including silicon, graphene, and flexible substrates, indicating its potential for use in the fabrication of electronic devices and interconnects [14].

One recent advancement in E-ALD of copper is the use of pulse deposition, which involves the deposition of short bursts of copper ions followed by a pause period. This technique has been shown to improve the uniformity and thickness control of the deposited copper film, resulting in a higher quality film. Another advancement is the use of additives in the copper ion solution, which can enhance the deposition rate and surface morphology of the copper film. For example, the addition of organic surfactants has been shown to improve the uniformity and adhesion of the deposited copper film.

Furthermore, recent research has focused on optimizing the E-ALD process parameters, including the potential, current density, and solution composition, to improve the quality and properties of the deposited copper film. For example, using a low potential and high current density has been shown to enhance the deposition rate and result in a smoother copper film. Moreover, the use of a copper sulfate solution with a low pH has been shown to improve the purity and electrical conductivity of the deposited copper film [15].

Recent advances

Improved electrode design:

Electrode design plays a crucial role in the performance of many electrochemical devices. Electrodes are the interface between the electrochemical system and the outside world, and they are responsible for the transfer of charge between the two. Electrode design is essential for achieving high efficiency and performance in many electrochemical applications such as batteries, fuel cells, and sensors. Electrode design involves a range of parameters, including the choice of material, the shape and size of the electrode, and the surface area available for electrochemical reactions [16].

The choice of electrode material is perhaps the most critical aspect of electrode design. The material must be stable, have good electrical conductivity, and be capable of facilitating the desired electrochemical reactions. For example, in lithium-ion batteries, the anode and cathode materials must be able to reversibly intercalate lithium ions, while in fuel cells, the electrodes must catalyze the desired reactions. The shape and size of the electrode also play a crucial role in its performance. The geometry of the electrode affects the surface area available for electrochemical reactions and can impact the transport of ions and electrons to and from the electrode. For example, in a battery, a thin electrode can improve the rate of ion diffusion and improve the overall performance of the battery.

Another critical aspect of electrode design is the surface area available for electrochemical reactions. The surface area of an electrode can be increased by various means, such as using a porous material or creating a rough surface. Increasing the surface area can enhance the electrochemical performance of the electrode by providing more active sites for electrochemical reactions. This is particularly important in electrocatalysis, where the electrochemical reaction occurs at the surface of the electrode. Increasing the surface area can improve the efficiency of the electrocatalytic reaction, leading to higher performance of the electrochemical device. In summary, electrode design is a complex process that involves a range of parameters, including material choice, electrode geometry, and surface area. Careful consideration of these factors is necessary to achieve high efficiency and performance in electrochemical devices.

Electrode design plays a crucial role in the success of the E-ALD (Electrochemical Atomic Layer Deposition) process. The deposition of high-quality films requires the use of suitable electrodes that are efficient and stable. With recent advances in electrode design, it is now possible to fabricate electrodes that can meet these requirements. The improved electrode designs have enabled E-ALD to achieve better control over film thickness and composition. This control is essential in achieving the desired properties of the films for various applications such as microelectronics, optics, and energy storage.

One of the key improvements in electrode design is the use of materials with high surface area, such as nanostructured electrodes. These electrodes have a high surface-to-volume ratio, which allows for a greater amount of surface reactions during the E-ALD process. The increased surface area also leads to better control over film thickness and composition. Nanostructured electrodes have been shown to produce high-quality films with improved properties, such as enhanced adhesion, higher density, and improved uniformity.

Another improvement in electrode design is the use of multi-electrode systems. In this design, multiple electrodes are used in a single E-ALD system, allowing for the deposition of different materials simultaneously. This method offers greater control over the deposition process and enables the fabrication of more complex film structures [17]. Multi-electrode systems are particularly useful in applications such as thin-film batteries and solid-state devices.

The development of composite electrodes is also a significant advancement in electrode design. These electrodes consist of two or more materials that are integrated to produce a composite structure. The composite structure enhances the electrochemical properties of the electrodes, resulting in higher efficiency and stability. Composite electrodes have been successfully used in the deposition of high-quality films for applications such as solar cells, sensors, and fuel cells.

Electrode designs that incorporate functional groups or coatings have also been developed. These designs enable the deposition of films with specific properties, such as increased conductivity or enhanced chemical stability. Functionalized electrodes have been used to fabricate films for a wide range of applications, including microelectronic devices and medical implants.

Underpotential deposition (UPD) is a phenomenon in electrochemistry where a metal is deposited onto another metal at a potential that is more negative than its normal deposition potential [18], [19]. This process occurs when the metal to be deposited forms a monolayer on the surface of the substrate metal by occupying the vacant spaces in the substrate's crystal lattice. The process of UPD has been extensively studied in the field of electrochemistry, and it has found a wide range of applications in the fields of catalysis, energy storage, and surface science. UPD is an important process in the field of electrochemistry, as it allows for the deposition of metals at very low potentials, which can be advantageous in various applications. For instance, UPD has been used to deposit metals onto electrodes in fuel cells, which helps to improve their catalytic activity and overall performance [20].

Development of new precursors:

Traditional precursors used in ALD were mainly inorganic, such as metal halides, alkoxides, or hydrides, which are often volatile and unstable, leading to poor film quality and low growth rates. In contrast, metal-organic precursors have emerged as a promising alternative, offering a wide range of advantages, including low vapor pressure, high thermal stability, and tunable chemical properties. Metal-organic precursors contain both metal and organic components that can be easily vaporized and transported to the deposition chamber. The organic ligands provide stability and solubility to the metal center, while the metal atom serves as a catalytic site for surface reactions [21].

One of the most significant advantages of metal-organic precursors is their ability to deposit a wide range of metal oxides and other complex materials. Metal oxides are essential materials for various applications, such as energy storage, catalysis, and electronics. For example, titanium dioxide (TiO2) is commonly used in solar cells, while hafnium oxide (HfO2) and zirconium oxide (ZrO2) are used in advanced electronic devices as high-k dielectrics. Metal-organic precursors offer a versatile platform to deposit these materials with high uniformity and conformality. In addition, metal-organic precursors can be modified to introduce other elements, such as nitrogen or carbon, to form metal nitrides or carbides, expanding the range of materials that can be deposited using ALD [22].

The self-limiting nature of ALD makes it an attractive technique for depositing highly uniform and conformal films. Metal-organic precursors undergo a series of self-limiting reactions, where each pulse of precursor introduces a controlled amount of metal or metal oxide onto the surface, and any excess precursor is eliminated by a purge gas. This self-limiting behavior enables precise control of film thickness and composition, leading to uniform films with high aspect ratios and conformality over complex three-dimensional structures. Moreover, metal-organic precursors have low decomposition temperatures, allowing for deposition at lower temperatures than traditional inorganic precursors, leading to less thermal stress and better film quality.

The use of metal-organic precursors has enabled the deposition of a wide range of materials with unique properties, such as high dielectric constants, high refractive indices, and excellent thermal stability. These materials have found applications in a variety of fields, including microelectronics, energy storage, and optics. Furthermore, the use of metal-organic precursors has enabled the deposition of materials that were previously challenging to deposit using other deposition techniques, such as metal oxides with high aspect ratios.

The development of new precursors has not only expanded the range of materials that can be deposited using ALD but has also allowed for the deposition of more complex structures. For example, the use of hybrid precursors containing both metal and organic components has enabled the deposition of materials with unique hybrid properties. These hybrid materials have found applications in a variety of fields, including catalysis, gas sensing, and biomedical applications [23].

The development of new precursors has also allowed for the deposition of materials with improved properties. For example, the use of precursor mixtures containing both metal and non-metal components has enabled the deposition of materials with improved mechanical properties, such as hardness and wear resistance. These materials have found applications in a variety of fields, including tool coatings, protective coatings, and biomedical implants [24].

Increased understanding of deposition mechanisms:

The field of E-ALD has greatly benefited from the increased understanding of deposition mechanisms. Advanced analytical techniques, such as in situ spectroscopy and microscopy, have allowed for a more comprehensive understanding of the deposition processes involved. By analyzing the deposition process in real-time, scientists can detect and address any issues or inefficiencies in the process. This has resulted in the development of more efficient and precise deposition processes that can produce high-quality thin films with excellent uniformity and control.

One of the benefits of the increased understanding of deposition mechanisms is the ability to control the thickness and composition of thin films. By analyzing the deposition process at a molecular level, scientists can determine the precise number of atoms being deposited and the composition of the thin film. This level of control allows for the creation of highly uniform and defect-free thin films, which are crucial for many applications in the electronics industry, such as the creation of thin-film transistors, sensors, and photovoltaic devices.

Furthermore, the increased understanding of deposition mechanisms has led to the development of new materials and deposition techniques. By understanding the chemical and physical processes involved in E-ALD, scientists can create new materials with improved properties and design new deposition techniques that are more efficient and environmentally friendly. This has led to advancements in various industries, such as the semiconductor industry, where the development of new materials and deposition techniques has enabled the production of smaller and more powerful electronic devices.

Another important benefit of the increased understanding of deposition mechanisms is the ability to optimize the deposition process. One of the key factors that affect the quality of the thin film is the deposition temperature. During the deposition process, the temperature of the substrate and the reactants can significantly impact the morphology, crystal structure, and chemical composition of the deposited film. For example, at low temperatures, the deposition rate may be slow, and the film may be amorphous, while at higher temperatures, the rate of deposition increases, and the film may crystallize. Therefore, controlling the deposition temperature is crucial to achieving the desired properties of the thin film.

In some deposition methods, such as PVD, an electric field is applied to the material to be deposited, causing it to vaporize and condense onto the substrate. The applied voltage can affect the energy of the vaporized material, which can influence the film's structure, adhesion, and composition. Additionally, the voltage can affect the ionization of the material, leading to the formation of unwanted impurities in the deposited film. Therefore, precise control of the applied voltage is necessary to obtain high-quality thin films.

The precursor concentration is another critical parameter that can significantly affect the quality of the thin film. Precursors are the materials used to create the thin film, and their concentration can impact the film's morphology, structure, and composition. For example, if the precursor concentration is too low, the deposition rate may be slow, and the resulting film may be thin and discontinuous. On the other hand, if the precursor concentration is too high, the resulting film may be too thick or may contain unwanted impurities. Therefore, optimizing the precursor concentration is necessary to achieve high-quality thin films. This allows for the optimization of the deposition process to produce thin films with improved properties, such as higher conductivity or better adhesion. Furthermore, the ability to optimize the deposition process can lead to cost savings by reducing the amount of precursor material needed and increasing the efficiency of the deposition process.

Advanced analytical techniques, such as in situ spectroscopy and microscopy, have provided a deeper understanding of the deposition mechanisms involved in E-ALD of copper. For instance, in situ infrared spectroscopy and in situ quartz crystal microbalance have been used to monitor the deposition process in real-time. These techniques have enabled researchers to study the surface chemistry and kinetics of the deposition process, which has resulted in the development of more efficient and precise deposition processes.

One of the significant advantages of E-ALD is its ability to deposit uniform and conformal films, which is critical for the fabrication of high-quality electronic devices. This technique uses alternating pulses of precursor and reducing agents, which react with the substrate surface to deposit a single atomic layer at a time. This process ensures precise control over the thickness of the deposited films and minimizes defects.

Integration with other techniques:

E-ALD, or plasma-enhanced atomic layer deposition, is a versatile and powerful technique for depositing thin films with precise control over thickness, composition, and properties. One of the key advantages of E-ALD is its ability to integrate with other techniques to create new materials and structures with enhanced properties and functionalities. For instance, E-ALD can be combined with surface modification techniques, such as plasma treatments or chemical functionalization, to tailor the surface properties of deposited films for specific applications. This can enable the creation of materials with improved adhesion, wettability, or biocompatibility, among others.

Another promising integration strategy for E-ALD is with atomic layer etching (ALE), which is a complementary technique for selectively removing thin layers with atomic-level precision [25] [4]. The combination of E-ALD and ALE can enable the creation of highly ordered nanostructures with precise control over their size and shape, which is critical for many applications in nanoelectronics, photonics, and catalysis. For instance, the use of E-ALD and ALE has been reported for the fabrication of nanoporous membranes, nanowires, and nanodots with tunable dimensions and properties. The resulting structures have shown improved performance in areas such as gas separation, sensing, and energy conversion.

In addition to ALE, E-ALD has also been integrated with other techniques such as physical vapor deposition (PVD), chemical vapor deposition (CVD), and solution-based methods to create hybrid materials and structures. For example, the use of E-ALD in combination with PVD has been reported for the fabrication of multilayer thin films with enhanced optical and mechanical properties. Similarly, the combination of E-ALD and CVD has been used to create nanocomposite coatings with improved wear resistance and hardness [26].

Integration of E-ALD with other techniques can also enable the creation of complex structures with hierarchical architectures, which can exhibit superior properties and performance compared to their homogeneous counterparts. For instance, the use of E-ALD in combination with microfabrication techniques has been reported for the fabrication of microfluidic devices with integrated nanoscale features, such as nanopores and nanochannels. The resulting devices have shown improved performance in areas such as biomolecule sensing and separation, as well as drug delivery and tissue engineering.

Moreover, the integration of E-ALD with advanced characterization techniques, such as in situ spectroscopy and microscopy, can provide insights into the growth mechanisms and properties of deposited films, which can facilitate the optimization and design of new materials and structures. For instance, the use of in situ spectroscopy techniques, such as Fourier-transform infrared (FTIR) spectroscopy and X-ray photoelectron spectroscopy (XPS), can provide real-time monitoring of the chemical reactions and surface species during the deposition process. Similarly, the use of in situ microscopy techniques, such as transmission electron microscopy (TEM) and scanning tunneling microscopy (STM), can provide insights into the morphology, crystal structure, and defect formation of deposited films at the atomic scale.

Applications in energy storage and conversion:

Energy storage and conversion have become essential components of modern society as the demand for clean and renewable energy continues to grow. The advent of atomic layer deposition (ALD) technology has revolutionized the field of energy storage and conversion by providing a precise and controlled method for depositing thin films of materials. One of the most promising variants of ALD is the electrochemical atomic layer deposition (E-ALD), which has shown great potential in the development of energy storage and conversion devices [27]. E-ALD offers precise control over film thickness and composition, which has enabled the development of high-performance electrodes and catalysts with improved durability and efficiency.

Batteries are one of the most widely used energy storage devices in the world, and E-ALD has played a significant role in improving their performance. E-ALD has been used to deposit thin films of materials such as lithium cobalt oxide and lithium manganese oxide, which are essential components of lithium-ion batteries. The precise control over film thickness and composition provided by E-ALD has improved the performance and durability of lithium-ion batteries, making them more efficient and long-lasting. Additionally, E-ALD has been used to deposit thin films of solid-state electrolytes, which can increase the safety and stability of lithium-ion batteries [28].

Supercapacitors are another energy storage device that has seen significant improvement with the help of E-ALD. Supercapacitors are high-capacity devices that can store and release energy quickly. E-ALD has been used to deposit thin films of materials such as manganese oxide and nickel oxide, which are essential components of supercapacitor electrodes. The precise control over film thickness and composition provided by E-ALD has improved the performance and durability of supercapacitors, making them more efficient and long-lasting.

Fuel cells are energy conversion devices that have also seen significant improvement with the help of E-ALD. E-ALD has been used to deposit thin films of materials such as platinum and palladium, which are essential components of fuel cell catalysts. The precise control over film thickness and composition provided by E-ALD has improved the performance and durability of fuel cells, making them more efficient and long-lasting. Additionally, E-ALD has been used to deposit thin films of solid-state electrolytes, which can increase the efficiency and stability of fuel cells.

The use of E-ALD in the development of energy storage and conversion devices has significant potential in addressing the global energy crisis. As the world becomes more reliant on renewable energy sources such as solar and wind power, there is a growing need for efficient and durable energy storage systems. E-ALD provides a cost-effective and precise method for the deposition of thin films, which can significantly improve the performance and durability of energy storage devices. Moreover, the technology can be used to develop new and innovative energy conversion devices that can provide sustainable and clean energy solutions.

One of the primary advantages of E-ALD is the ability to deposit thin films of materials with precise control over thickness and composition. This capability enables the development of high-performance energy storage and conversion devices with improved durability and efficiency. E-ALD has also been used to create multi-layered films with different compositions, which can further enhance the performance of energy storage and conversion devices. The use of E-ALD technology in the development of energy storage and conversion devices has the potential to revolutionize the field and provide sustainable solutions for the energy needs of the future.

Conclusion

Improvements in electrode design have led to significant advancements in E-ALD. The use of materials with high surface area, multi-electrode systems, composite electrodes, and functionalized electrodes have enabled the deposition of high-quality films with improved properties. These advancements have opened up new possibilities for the development of advanced materials and devices for various applications, including microelectronics, optics, and energy storage.

The development of new precursors has allowed for the deposition of materials with tailored properties. For example, the use of precursor mixtures containing both metal and organic components with different functional groups has enabled the deposition of materials with tailored surface chemistry. These materials have found applications in a variety of fields, including biomaterials, sensors, and microelectronics. The ability to tailor the surface chemistry of deposited materials opens up new avenues for designing materials with improved functionality and performance.

The increased understanding of deposition mechanisms in E-ALD has had a significant impact on the field [29], leading to the development of more efficient and precise deposition processes, the ability to control the thickness and composition of thin films, the creation of new materials and deposition techniques, and the optimization of the deposition process. These advancements have enabled the production of high-quality thin films with improved properties, which have applications in a wide range of industries, including electronics, energy, and catalysis.

The integration of E-ALD with other techniques represents a powerful strategy for developing new materials and structures with enhanced properties and functionalities. The versatility and precision of E-ALD, combined with the complementary nature of other techniques, can enable the creation of complex structures with hierarchical architectures, as well as the optimization and design of new materials for specific applications. Moreover, the integration of E-ALD with advanced characterization techniques can provide insights into the growth mechanisms and properties of deposited films, which can further facilitate the development of new materials and structures with tailored properties and performance.

The development of energy storage and conversion devices is essential in addressing the global energy crisis. E-ALD has shown great promise in the development of high-performance energy storage and conversion devices such as batteries, supercapacitors, and fuel cells. The precise control over film thickness and composition provided by E-ALD has enabled the development of high-performance electrodes and catalysts with improved durability and efficiency. The technology can also be used to create new and innovative energy storage and conversion devices, providing sustainable and clean energy solutions for the future.

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