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A review on; Thin Film Preparation of Nanomaterials: Deposition Techniques, Properties, and Applications

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Abstract: Nanomaterials in the form of thin film form indispensable parts of modern technological world including microelectronics, optoelectronics, energy conversion and storage, sensors, and various biomedical devices. The active fabrication of the nanostructured thin films gives a fine-tuning of the structural, optical, electrical and mechanical properties on a nanoscale. The review compiles a broad overview of the principle, taxonomic groupings, and the most current developments in respect to the thin film preparation technique of nanomaterials. The main deposition modalities such as physical vapor deposition, chemical vapor deposition, sol-gel processing and electrochemical are analyzed in details. Techniques of characterization, salient functional properties, major application, ongoing challenges, as well as future research directions, are also outlined.

Keywords: *Nanomaterials; Thin films; Physical vapor deposition; Chemical vapor deposition; Sol -gel method; Characterization.*

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Introduction

Quantum confinement effects, an increased surface-volume ratio, and a change in electronic structures characterize the physicochemical properties of nanomaterials (at least one dimension of 1-100nm) compared to their bulk counterparts. The unique properties have made nanomaterials to be at the forefront of investigation in the fields of material science, physics, chemistry, and engineering. Nanotechnology has advanced at a rapid pace during the past decades, and nanomaterials have been utilized as functional systems and as a means of integration into such systems, and to this end the use of thin films which are recognized to be the most important building block of modern technology is most frequently utilised.

Thin films refer to layers of materials of thickness of a few nanometres to multifew micrometres and deposited on appropriate substrates. In cases where nanomaterials are developed into thin films, they can be developed with a fine control of their properties by regulating the thickness, grain size, crystallographic orientation, porosity and surface roughness. The variables have a significant effect on optical absorption, electrical conductivity, mechanical strength, and chemical reactivity. As a result, nanostructured thin films have found their way in the application in microelectronics, photovoltaics, sensing and protective surfaces.

The increased surface area caused by the thin films of nanomaterials is among the most outstanding benefits of nanomaterials in surface-based processes like catalysis, gas sensing, electrochemical reactions, etc. Quantum confinement in thin films of semiconductor provides tunable band gaps and enhanced chargecarrier dynamics in semiconductor thin films, realizing the creation of high-performance electronic and optoelectronic devices. Similarly, nanostructured oxide films have provided higher sensitivity and selectivity when used as gas-sensors because more adsorption sites and high rates of surface-reaction were enhanced.

The nanomaterials in the form of thin films are used in energy related fields such as photovoltaics, batteries, and supercapacitors. Nanostructured thin films in solar -cell architectures have been proposed as light -absorbing layers, charge -transport materials, or barrier coats, which enhance power -conversion efficiency and stability. In batteries based on Lithium-ion and supercapacitors, nanomaterials used as thin-film electrodes offer shorter ionic diffusion routes, higher specific surface area, and increase the cycling lifetime of bulk analogues. These factors highlight the critical importance of thin-film engineering in addressing the issue of energy facing the world.

Out of the energy and electronics sectors, nanomaterial thin films have received significant interest in fields of biomedical and environmental. Thin films based on biocompatible materials are also extensively used as medical implantation Coatings to enhance corrosion resistance, wear resistance, and biological adhesion. Besides, the functionalised nanofilms are incorporated in the biosensing systems to detect biomolecules, pathogens and environmental pollutants with high sensitivity and rapid response. The ability to design surface chemistry and morphology on a nanoscale makes thin-film nanomaterials particularly well adapted to such applications.

The quality and stability of the nanomaterial thin films is directly related to the method applied when they are being deposited. Various types of physical, chemical, and electrochemical deposition strategies have been designed in order to achieve a controlled film growth with desirable structural and functional characteristics. Deposition rate, substrate temperature, ambient pressure and post deposition treatment are also parameters that determine microstructure, crystallinity and adhesion decisively. Therefore, a comprehensive understanding of the methods of preparation of thin-films is essential when it comes to optimizing material performance and ensuring the reproducibility of the same in real-life scenarios.

In spite of significant advances, there are still barriers in terms of massive fabrication, homogeneity, stability and attachment of nanomaterial thin films to existing technologies. Film stress, interface consistency and environmental degradation are still limiting commercial adoption. The overcoming of these hurdles requires methodological examination of growth processes, sophisticated characterisation techniques, and the establishment of cost effective, environmentally harmless deposition procedures.

In this regard, the current review is aimed at providing a thorough picture of the nature of the groundwork aspect of nanomaterial thin films, especially in terms of the preparative methods, structure-property relations, and its primary applications. Having condensed the latest developments and identifying the existing issues, this review should become a useful source of information to those researchers and engineers who are engaged in the sphere of thin-film nanotechnology.

Result and discussion

Thin Films and Nanostructured Materials

Thin films are sheets of material whose thickness is a few nanometres to a few micrometres and is deposited on a proper substrate. In such situations when the films are arranged on the nanoscale, they are known as nanostructured thin films and can include nanocrystals, nanoparticles, nanocomposites or nanoporous architectures. Having a lower dimensionality, as well as high surface-to-volume ratio, imparts unusual physical and chemical behavior that is no longer reminiscent of bulk materials.

The grain size, crystallinity, defect density, surface roughness and interfacial characteristics between the film and substrate are conceivably the important parameters of nanostructured thin films on the basis of their functional behaviour. They affect directly optical absorption, electrical conductivity, mechanical stability and chemical reactivity. As a result, a detailed comprehension of the underlying nucleation and growth process in the course of forming films is crucial towards gaining control on the microstructure of films and attaining thin films of high-quality and characteristics which are applicable to specific tasks.

Techniques of Thin Film Deposition.

Physical Vapor Deposition (PVD) is utilized in the production of metals (Nelson and Cox 1) 3.1 Physical Vapor Deposition (PVD).

Physical vapor deposition (PVD) is a group of technologies based on a vacuum in which a solid source of material is transported onto a substrate through vaporisation and condensation. There are common techniques of PVD such as thermal evaporation, electron-beam evaporation and sputtering. Such methods have been commonly used to deposit metallic, semiconductor and oxide nanomaterial thin films due to their high purity and strong adhesion properties.

Thermal Evaporation:

In thermal evaporation, the material to be evaporated is heated to a high vacuum temperature. The evaporated atoms or molecules pass through the vacuum and fall on the surface of the substrate to create a thin film. The method is especially appropriate with metals and materials of relatively low melting points, but provides limited control of stoichiometry of films of multi-component systems.

Sputtering:

Sputtering is the impact of active ions on a target material, which is usually produced in a plasma. The effect of these ions is that it removes atoms through ejection of atoms off the target and then fall onto the substrate to create a thin film. Compared to thermal evaporation, sputtering provides a better control of film thickness and composition as well as uniformity. Also, sputtered films tend to have a high level of adhesion and high density of microstructure making this method applicable to a wide range of nanostructured materials.

CVD involves the growth of deposits through the reaction of chemical gases (Mikalaucik et al. 2008

3.2 Chemical Vapor Deposition (CVD) Chemical Vapor Deposition is the formation of deposits by a reaction between chemical gases (Mikalaucik et al. 2008).

The chemical vapor deposition (CVD) is a deposition process that relies upon chemical reactions of gaseous precursors around or directly on a hot substrate surface, and that results in the formation of a solid thin film. Other forms of CVD that have been widely used to deposit semiconductor, oxide, and carbon based nanomaterials include plasma enhanced CVD (PECVD) and metal-organic CVD (MOCVD).

The CVD methods are infamous due to their high uniformity of the film, deposition levels, and their ability to produce conformal coatings on non-planar and geometries with high aspect ratios. These characteristics make CVD especially appealing as a microelectronics, optoelectronics, and protective coating film.

Sol -Gel and Solution-Based Methods

Solgel processing is a cost saving and all round solution-based method of fabricating thin-film. It is done by preparing a colloidal solution (sol) of metal alkoxides or inorganic salts and then, some deposition methods are carried out which include spin coating or dip coating. Further drying and heat treatment converts the sol into a thick film in the form of dense or porous gel. Sol-gel techniques have been extensively applied in the deposition of thin films of oxide nanomaterials including TiO 2, ZnO, and SiO 2. These methods have compositional flexibility, coating areas, and low processing temperatures. However, film cracking and shrinkage during heat treatment are some of the challenges that should be handled with a lot of care.

Electrochemical deposition involves the application of electrochemical processes to deposit a plated coating on a surface or object (Wikipedia, 2011).

Electrochemical Deposition

ECD is the use of electrochemical reactions to plate a coating on a surface or object (Wikipedia, 2011).

Electrodeposition or electrochemical deposition involves reduction of metal ions in an electrolyte solution on a conductive substrate in an electric potential. This method allows a fine regulation of the film thickness, composition and morphology through control of deposition parameters (current density, electrolyte concentration, deposition time). Electrochemical deposition is especially desirable as it has a low processing temperature, costs, and is applicable in the deposition of nanostructured metallic and composite thin films. It is widely used in the sensors, corrosion resistant coating, and energy storage devices.

Characterization Techniques

Thin films of nanomaterials should be characterised thoroughly to ensure that there is a clear portrayal of the relationship between deposition parameters, microstructure, and functionality. Since the properties of thin films are of great importance with regard to their thickness, crystallinity, surface morphology and interfaces, a blend of supplementary characterisation methods is often used. Structural, morphological, compositional and optical analysis gives essential information about the quality of the film and allows optimisation of the fabrication processes to be used in a specific application.

X-ray Diffraction (XRD)

The most common techniques that have been extensively used as far as structural characterisation of nanostructured thin films is concerned include the use of X-ray diffraction (XRD). It is mainly used in phase identification, determination of crystallographic structure and analysis of preferred orientation (texture) in the film. It is possible that XRD patterns allow the determination of crystalline phases and determine the purity of the film through comparison with standard reference data.

Also, the XRD technique can be used to estimate crystallite size and lattice strain as a mean based on the peak-broadening equation, like the Scherrer equation. The difference in peak intensity and position is used to provide information on residual stress, lattice distortion and film-substrate interactions. The parameters are especially important in the perception of growth mechanisms and their effects on the electrical, optical, and mechanical properties.

Scanning Electron Microscopy (SEM)

The scanning electron microscopy (SEM) is widely used to analyse the surface morphology as well as microstructural character of the thin films. SEM can give high-resolution images that give information about the grain size, grain boundaries, surface homogeneity and presence of defects like cracks or pores. The thickness of the film and the continuity of layers can be measured by using cross-sectional SEM imaging.

The use of SEM in conjunction with energy-dispersive X-ray spectroscopy (EDS) allows performing a qualitative and semi-quantitative analysis of elements, which allows assessing film composition and homogeneity. SEM analysis particularly is useful in the correlation of deposition parameters with morphological evolution and growth behaviour.

Transmission Electron Microscopy (TEM) was used to examine the cells at 80keV

The cells were examined using Transmission Electron Microscopy (TEM) at 80keV (4.3).

Transmission electron microscopy (TEM) provides a detailed information of internal microstructure of nanomaterial thin films at atomic and nanoscales. TEM is capable of showing crystallographic orientation, grain boundary, dislocations and interfaces between the film and substrate. Direct visualization of lattice fringes is made possible by the high-resolution TEM (HRTEM), which is capable of giving accurate data on the crystal structure and defects. Patterns of selected -area electron diffraction (SAED) acquired in the course of TEM analysis are used to establish crystallinity and phase structure. Applicability TEM is especially significant in the review of ultrathin films, multilayer structures, and nanocomposites, in which the interfacial properties of the material play a vital role in performance.

Atomic Force Microscopy (AFM)

Atomic force microscopy (AFM) is an effective surface characterisation method, which is applied to assess surface roughness, topography, and nanoscale of thin films. However, in comparison to electron microscopy, AFM does not require conductive samples or vacuum conditions, which means that it is applicable to a broad variety of materials, such as polymers and biological coating. The AFM produces three dimensional surface profiles at nanometer scale resolution, and the quantitative approach to the analysis of the parameters, such as root-mean-square (RMS) roughness and grain-size distribution is possible. The optical scattering, adhesion, wettability and electrical contact behaviour of thin-film devices largely depend on surface roughness.

UV-Visible Spectroscopy

To study the optical properties of thin films that are nanostructured, UV - visible spectroscopy is often used. Absorbance and transmittance spectra measurements can be used to obtain the data on optical transparency, absorption coefficient, and optical band gap. Tauc plots calculated based on the absorption data are usually used to estimate the band gap energy. Optical characterisation is especially significant to be applied in optoelectronics, photovoltaics and transparent conductive coating. Change in optical behaviour can be related to the film thickness, crystallinity and defect concentration, which gives useful information of the effects of the deposition conditions on optical performance.

Characteristics of Thin Films of Nanomaterial

Electrical Properties

The nanostructured thin films have size-dependent electrical conductivity, mobility of carriers, and dielectric behaviour, which make them appropriate to use in electronic and sensor technology.

Optical Properties

Nanomaterials in thin films exhibit a higher optical absorption, photoluminescence and controllable band gaps, which are vital in optoelectronic and photovoltaic devices.

Mechanical Properties

Compared to bulk materials, nanocomposites and multilayered thin films are frequently more hard, wear resistant, and mechanically stable.

Applications

Electronic and Optoelectronic devices 6.1 Electronic and Optoelectronic devices.

Nanomaterial thin films are used in transistor, light emitting diode, and integrated circuits.

Conversion and storage of energy

The thin-film nanomaterials are major applications in the solar cells, lithium-ion batteries, supercapacitors, and fuel cells.

Sensors and Biomedical Applications

Nanofilms with high surface area are used in gas sensors, biosensors, corrosion resistant coating and biocompatible implant surfaces.

Difficulties and Future Projections

Even after tremendous improvement, issues are still faced in large scale fabrication, long term stability, reproducibility and compatibility with flexible substrates. It is anticipated that future studies will be based on the 2-D materials, hybrid nanostructures, and environmentally friendly processes of deposition.

Conclusion

The preparation of nanomaterials by thin-film is an area that is in the process of rapid development with significant scientific and technological impact. Improvements in deposition processes and characterisation procedures have made possible strict control of the characteristics of the thin-films. Further development of research will expand their uses in the next generation devices**.**

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