Metal Oxide Nanostructures-Based Electronics

Manoj Dey, Nikhilesh Maity, and Abhishek K. Singh

Abstract Metal oxide nanostructures have garnered significant attention in recent years due to their unique physical, chemical, and electrical properties. One of the inherent advantages of oxide nanostructures is their high surface area-to-volume ratios, which enable improved charge carrier transport and device performance. In this chapter, we provide an overview of metal oxide nanostructures and their potential applications in solar cells, displays, water splitting and cleaning, memory devices, bioelectronics, etc. We cover the synthesis and characterization of these materials, in addition to their advantages over traditional nanostructures. The chapter also discusses the challenges of metal oxide nanostructures in micro- and nano-electronics, along with future research goals. Overall, this chapter provides a comprehensive overview of the current state of the field and the potential of metal oxide nanostructures for advancing electronics technology.

Keywords Metal oxides · Nanostructures · Modern electronics · Electronics devices · Quantum effects · Field-effect transistors · CMOS technology

1 Introduction

According to Moore's law, the density of transistors in an integrated circuit becomes two-fold in two years, leading to a corresponding increase in processing power and a decrease in cost per transistor [1]. However, as transistors continue to shrink, it is becoming increasingly difficult and expensive to manufacture them, and there are

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concerns that Moore's Law may be reaching its limit. Achieving multi-functionality and diversity in electronic devices is the long-term future goal. Therefore, it is timely to investigate the possibility of emerging new materials and even new methods in building electronic devices. In this aspect, metal oxide (MO) nanostructures possess both novel quantum effects and excellent semiconductor properties that make them promising materials for electronics [2]. Moreover, MO nanostructures are deemed a major element in the development and building of many nanoelectronics devices due to their extraordinary electrical, physical, and chemical properties [3]. MO nanostructures have also gained significant attention due to their potential to solve various global issues, particularly in the biomedical and environmental fields [4]. Recent developments in these areas include the use of MO nanostructures in drug delivery systems, gas sensors, and improved medical diagnostic accuracy [5]. Additionally, MO nanostructures have also been used in personal care products [6], energy storage [7], and paint & coating industries [8]. These nanostructures exhibit excellent optical and electrical properties, are capable of being transparent, can be applied to large areas, and possess a high level of mechanical flexibility. Additionally, the properties of MO nanostructures can be tailored to meet the demands of different applications by adjusting their morphology. With environmental concerns at the forefront of research, it is essential to prioritize low-cost, sustainable materials and methods that can still provide high integration and performance levels. In this regard, non-critical metal oxides like ZnO and TiO_2 have demonstrated their ability to meet the requirements of multi-functionality while being environmentally friendly [9]. MO nanostructures possess a wide range of exotic and innovative quantum properties, including ferroelectricity, piezoelectricity, thermoelectricity, and magnetostriction [2]. These properties make MO nanostructures suitable for various applications, such as data storage, actuators, biosensors, wearable electronics, displays, and smart windows [2]. Despite having many advantages, MO nanostructures also have several limitations that restrict their use in modern nano- and micro-electronics. In recent years, researchers have focused on developing novel methods to synthesize MO nanostructures, and using computational methods to study their microstructures and predict macro-level properties [4, 10]. A deeper understanding of the relationship between microstructure and exotic properties can lead to improved performance and functionalities in modern electronic devices. This can also open up the possibility of designing and fabricating MO nanostructures to meet specific electronic applications.

In this chapter, we will discuss recent advancements in the fabrication, analysis, and potential applications of MO nanostructures from both a structural and application perspective in modern electronic devices. We arrange this chapter as follows. In Sect. 2, we will explore several state-of-the-art synthesis and characterization methods for fabricating oxide nanostructures of different dimensions. The exotic properties of oxide nanostructures which make them potential for modern electronics, will be discussed in Sect. 3. In the subsequent Sect. 4, we will review various classes of oxide nanostructures and their applications in electronic devices. Finally, we will discuss several challenges and future directions of electronics in the concluding section. These discussions will serve as a foundation for developing new MO nanostructures with improved performance for electronic device applications.

Additionally, this chapter will provide a platform for translating scientific discoveries into practical multi-functionalities.

2 Synthesis and Fabrication

Device fabrication from metal oxide nanostructures is greatly dependent on their dimensionality, composition, morphology, and uniformity of nanostructures. Therefore, different top-down and bottom-up approaches (see Fig. 1) have been developed to control the growth mechanism over the years. The top-down process starts with macroscopic structures and incorporates external control of nanostructure production. This method utilizes state-of-the-art milling and nanolithography techniques to insert or eliminate thin layers from bulk materials. In contrast, the bottom-up approach involves reducing materials components to the atomic level and then utilizing physical forces to make self-assembly into larger, stable structures. By organizing atomic or molecular components hierarchically, complex nanostructures are formed. For instance, semiconducting oxide nanostructures synthesis in nanowires morphology using chemical vapor deposition (CVD). These experimental techniques offer control over atomic and electronic structures, particle size, microstructures, morphology, and dimensionality. The state-of-the-art synthesis methods and characterization techniques are discussed below for fabricating different dimensional metal-oxide nanostructures.

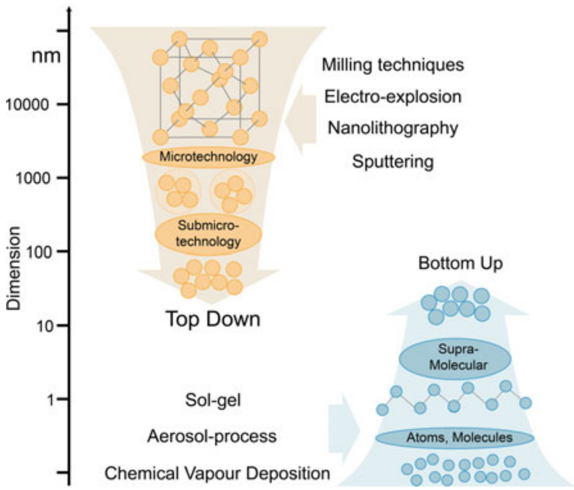

Fig. 1 Top-down and bottom-up approaches for the synthesis of metal oxide nanostructures

2.1 0D Nanostructures

Zero-dimensional (0D) metal-oxide nanostructures include nanoparticles, nanoclusters, and quantum dots with particle sizes within a few nanometers. Device fabrication from 0D nanostructures is advantageous owing to the large surface-to-volume ratio and a low surface area between nanoparticle and surface. Depending upon the preparation technique, nanoparticles can be characterized with different morphologies, such as cube, sphere, octahedron, decahedron, etc. Solvothermal, liquid-phase reduction, and electrochemical deposition techniques are commonly used for 0D nanostructure characterization. The solvothermal method uses solvent under moderate to high temperature and pressure to facilitate the heterogeneous reaction. Water is a widely used solvent, especially for metal-oxide nanostructure characterization, then this method is termed "hydrothermal synthesis". By controlling the growth temperature, concentration, and reaction time, different morphological 0D nanostructures can be characterized by hydrothermal methods. After the arrival of the atoms, nanostructure growth happens in three steps,

(i) surface diffusion, (ii) nucleation, and (iii) layer-by-layer deposition. The hydrothermal method is a simple and cost-effective method for nanostructure characterization. This method is successfully implemented to characterize ZnO quantum-dots and nanocrystals [11], Fe_3O_4 nanocrystals [12]. Metal-oxide nanoparticles can also be directly obtained in liquid-phase reduction by using different soluble precursors in a solvent. Noble metal loaded metal-oxide nanostructures (such as Pt/TiO_2), which are very good catalysts, can be synthesized by liquid-phase reduction techniques [13]. Electrochemical deposition uses an electrode possessing a solid-liquid-gas triphase. Aqueous solution can trap gas pockets while exposing the liquid surface to a solid/gas interface. This electrode helps to create locally high interface pH value independent of bulk conditions, thus, beneficial for depositing metal-oxides in robust electrolytes [14]. Pure phase of Cu_2O [14] and ZnO [15] in the 0D nanostructured form are synthesized by using this method.

2.2 1D Nanostructures

Metal-oxide nanostructure with the morphology of nanowires, nanotubes, nanofibers, and nanobelts have received much attention due to its capability of surface functionalization for tailoring superior properties and device applications. Liquid-phase growth and vapor-phase growth are very important methods for 1D metal-oxide nanostructure synthesis. The liquid-phase deposition technique relies on the chemical equilibrium of the metal-oxide and metal-fluoro complexes. Therefore, uniform 1D nanostructures with large surface areas and complex morphologies are fabricated on different substrates. Moreover, the multi-component 1D nanostructure can also be synthesized as it uses a homogeneous liquid-phase. This process is also known as a template-based synthesis process, as 1D nanostructures can be grown as templates in confined spaces. $CoFe_2O_4$ nanowires [16], Ni nanopillar in TiO_2 surface [17], and VO_2 nanotube arrays [18] are successfully synthesized using the liquid phase technique in the sol-gel template. In general, vapor-phase growth can be classified into physical and chemical deposition processes. Physical vapor deposition (PVD) includes vacuum evaporation and sputtering, in which bulk metal-oxide sublimate into vapor and further condensate into nanostructures. In chemical vapor deposition (CVD), on the other hand, vapor-solid chemical reaction takes place in the vicinity of pre-heated substrate surface. Therefore, the preferable growth of nanostructures can be achieved by controlling the flow rate and precursor partial pressure. CVD is the most widely used technique for the growth of semiconductor nanowires such as Ga_2O_3 [19], Fe_2O_3 [20], SnO_2 [21], In_2O_3 [22], MgO [23], SiO_2 [24].

2.3 2D Nanostructures

Two-dimensional (2D) nanostructures have gained significant attention owing to their intrinsic layered atomic structures and electron confinement. 2D nanostructures play a crucial role in improving the efficiency of surface-enhanced processes, including catalysis and sensing. Pulsed laser deposition (PLD) and magnetic sputtering are the widely used methods for the preparation of 2D metal oxide nanostructures. A high-energy laser pulse is shot in a rotating target material consisting of the desired substrate in preheated or room temperature conditions in the PLD method. The plasma created by the laser ablation process on the substrate then adiabatically expands on the vacuum chamber and further condensates as a thin film. PLD is used to prepare high-quality thin film for device application, especially for gas sensing [25]. Magnetron sputtering processes use high-energy particles to bombard target material, which then eject atoms or molecules. The ejected atoms or molecules are then deposited on the substrate to create superlattices or nanofilms. Magnetron sputtering produces high-purity uniform thin films over a large area due to the high deposition rate and ability to sputter metal, alloy, or compound. These processes are generally termed top-down approaches (as shown in Fig. 1). WO_3 [26], TiO_2 [27], and ZnO [28] nanofilms are examples of metal oxide nanostructures produced by PLD method. Another widely used thin film deposition technique known as atomic layer deposition (ALD) involves sequentially exposing a substrate to a number of gas-phase chemical precursors. These precursors interact with the substrate's surface to create a thin coating of the desired substance. ALD is a thin film deposition technique that is highly reliable and controlled, and it is frequently used to create 2D nanostructures. Atomic layer deposition (ALD) is commonly used to fabricate high-k gate dielectrics (like Al_2O_3, HfO_2, and ZrO_2 [29]). Molecular beam epitaxy (MBE) whereas uses a beam of atoms or molecules to deposit thin films of a material onto a substrate in a vacuum chamber. The beam is directed onto the substrate using magnetic or electric fields, allowing precise control over the film thickness and composition. As a result, MBE is an excellent choice for creating heterostructures, heterointerfaces, and complex oxide films of high quality [30]. Recently, Lithography and self-assembly techniques are also becoming famous, especially for the fabrication of chemical and biomedical oxide nanostructured materials [31].

3 Unique Properties of Metal Oxide Nanostructures

MO nanostructures have a number of unique properties that make them interesting for a wide range of applications, including electronics. Some of the key properties (shown in Fig. 2) of MO nanostructures include:

High surface area: One of the most important properties of oxide nanostructures is their large surface area, which is responsible for many of their distinct characteristics and prospective uses. The high surface area makes oxide nanostructures ideal for catalytic and other surface-based applications, as they provide a large number of active sites for chemical reactions to occur [32]. Furthermore, the high surface area of oxide nanostructures can contribute to their high stability and chemical resistance by allowing for strong chemical bonding on the surface.

Quantum effects: The electronic characteristics of nanostructures vary significantly from their bulk phase when the crystal size is equivalent to the de Broglie wavelength of electrons because of the quantum confinement effect [33]. When the dimension is lowered, the inter-band transition and carrier mobility are impacted, as is the bandgap of the nanostructure. In general, the band gap widens and has an inverse relationship with the dimension of nanostructures in diverse morphologies such as nanowires, nanofibres, quantum dots, etc.

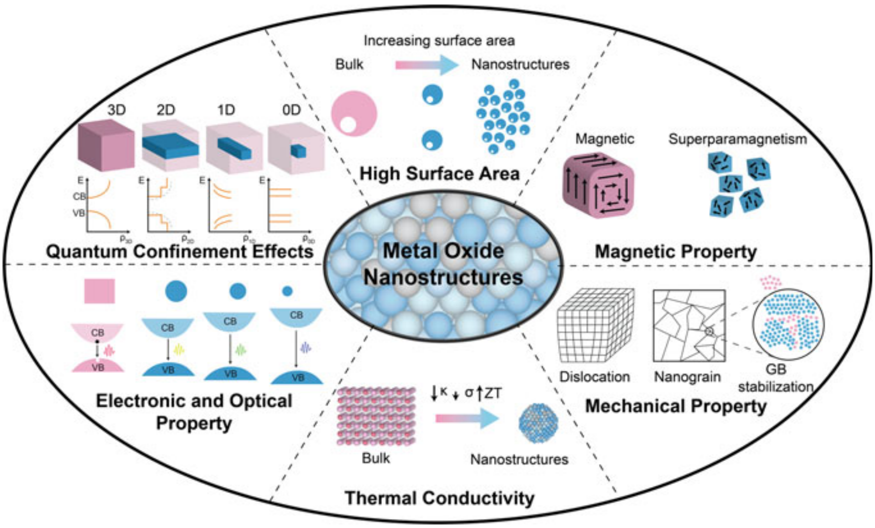

Fig. 2 Schematic representation of several exotic properties of metal-oxide nanostructures

Electrical and Magnetic properties: The electrical and magnetic characteristics of oxide nanostructures highly depend on their size and structural morphologies, and they differ significantly from their bulk counterparts. Oxide nanostructures have distinct electrical characteristics that can be used in a wide range of applications. Some oxide nanostructures, for example, have a high dielectric constant, making them suitable as insulating materials in electronics. Others have low resistance and are suitable for use as conducting materials. The specific electrical properties of an oxide nanostructure depend on its specific chemical composition, size, shape, and surface properties. Similar to this, certain oxides—like iron oxide (magnetite), for example—can be used to make magnetic nanostructures since they are inherently magnetic. Other oxides—like alumina (aluminum oxide), can be made magnetic by adding magnetic impurities or by subjecting them to a magnetic field, even if they are not magnetic by nature [34]. This provides a lot of flexibility when designing devices for specific electronic applications.

Thermal conductivity: Due to their distinctive physical and chemical characteristics, oxide nanostructures exhibit exceptional thermal conductivity. At the nanoscale, oxide materials have a greater surface area-to-volume ratio, which can help with phonon scattering and the transmission of heat [35]. Strong covalent bonds are another factor in the heat conduction of many oxide materials. Many different applications, including the creation of electrical devices and heat management systems, frequently employ these materials.

Mechanical properties: Oxide nanostructures have high strength and stiffness, fracture toughness, and low ductility due to their small size, high surface area, and strong covalent bonding [36]. The mechanical properties of oxide nanostructures make them suitable for use in electronic devices that require structural stability, wear resistance, and hardness. However, their low ductility and brittle-ductile transition temperature may limit their use in certain applications.

These characteristics have made oxide nanostructured materials beneficial for a variety of applications, significantly improving the performances of numerous technologies. The following discussion will provide detail about various oxide nanostructures, their characteristics, and their uses in electronic technologies.

4 Applications of Metal Oxide Nanostructures in Electronics

4.1 Graphene Oxide Based Electronics

Graphene, a single-layer or few-layer carbon allotrope, has emerged as a subject of intense research and technological interest due to its extraordinary physical and chemical properties [37]. As a conducting semimetal, graphene has revolutionized electronics, sensing, and energy storage devices. The single or few layer thick graphite oxide and its reduced form i.e., graphene oxide (GO) and reduced graphene

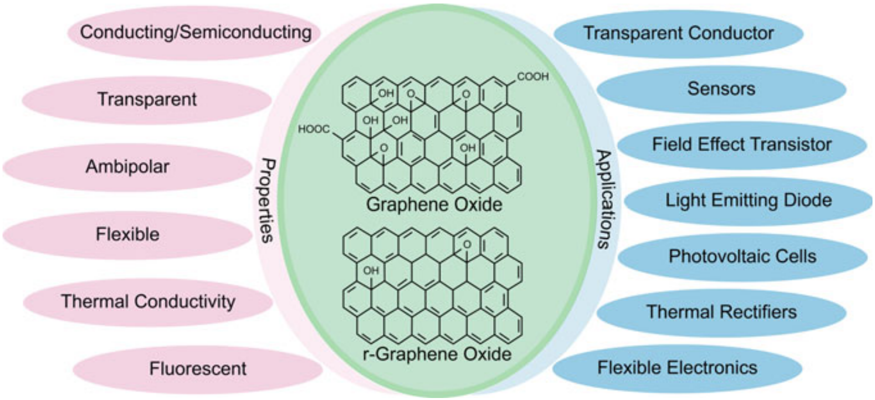

Fig. 3 Properties of graphene oxide and reduced graphene oxide and their applications in modern electronics

oxide (rGO) has also been explored as emerging materials for electronic applications because of their unparalleled advantages over graphene [38, 39]. The GO in pristine form shows low electrical conductivity leading to insulating or semi-conductive behavior depending on the degree of oxidation. However, it can be reduced to form conductive reduced graphene oxide (rGO) using various methods. The exotic properties and applications of graphene oxide and reduced graphene oxide nanostructures are depicted in Fig. 3. Chemical reduction, hydrothermal, plasma, and microwave methods are widely used synthesis techniques for GO and rGO synthesis.

By controlling the degree of oxidation or introducing defects or dopants into the material, GO can also be modified to become a conductor, which makes GO, along with rGO, promising materials for use in transistors [40], sensors [41], and energy storage devices [42]. Additionally, the excellent mechanical properties, including high tensile strength and flexibility [43] of GO and rGO make them ideal materials for use in flexible electronics, such as wearable devices and flexible displays [44]. The chemical stability and biocompatibility of GO are suitable for use in a variety of applications, including drug delivery systems [45] and bioelectronics [46]. The GO can also serve as transparent conductor in electronic devices such as touch screens [47] and solar cells [48]. However, the large-scale production of high-quality graphene derivatives remains a technological challenge. The complexity and expense of synthesizing and purifying graphite, along with controlling the degree of oxidation, composition, and size, are obstacles to the widespread industrialization of graphene oxide-based nanostructure electronics.

4.2 Ferroelectric Oxide Nanostructures

Ferroelectric oxide nanostructures, possessing the ability to switch between two thermodynamically stable electrical states of opposing ionic polarization, have been utilized in a wide range of electronic devices such as sensors, actuators, flash drives, and solid-state drives [49]. High dielectric constant of ferroelectric oxide nanostructures enables them to store a large amount of electrical charge. Ferroelectric oxide nanostructures generally include perovskites (such as $BaTiO_3$, $SrTiO_3$, $BiFeO_3$, $PbZr_xTi_{1-x}O_3$) and layered perovskites ($Bi_4La_4Ti_3O_{12}$, $SrBi_2Ta_2O_9$) materials [49]. These materials can be synthesized in the form of thin films, nanoparticles, or other nanostructures through various techniques, including pulsed laser deposition, sol-gel processing, and chemical vapor deposition [51]. Due to their ease of incorporation into nanostructures, ferroelectric materials allow the integration in ultrahigh nanoscale nonvolatile memory devices (NVMDs) such as nonvolatile ferroelectric field effect transistor (FeFET) [52] (see Fig. 4).

In addition to their practical applications, ferroelectric oxide nanostructures are also intriguing to researchers studying fundamental phenomena such as ferroelectricity and ferromagnetism at the nanoscale. The ability to fabricate and study these materials at the nanoscale has opened up new possibilities for understanding and exploiting their unique properties. However, a number of intrinsic difficulties, including fatigue, endurance, and charge retention time, restrict the deployment of ferroelectric nanostructures [53, 54].

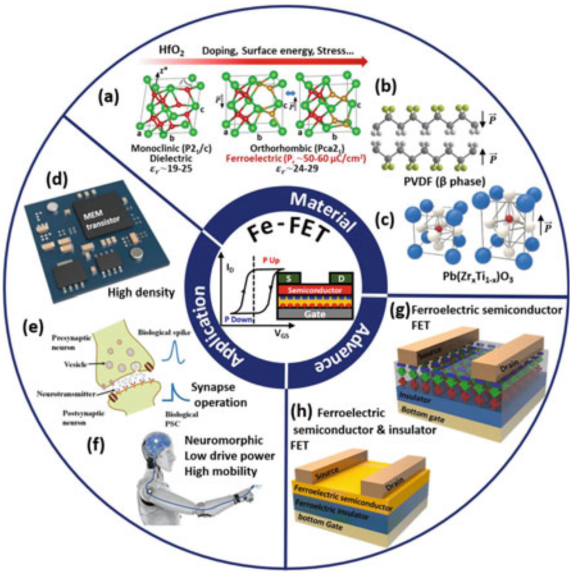

Fig. 4 Applications of Ferroelectric metal oxide nanostructures in FeFET. Reprinted from Ref. [50], with the permission of AIP Publishing

4.3 Piezotronics

Piezoelectric semiconductor in low-dimensional nanostructure morphology possesses exceptional mechanical properties and can be incorporated into flexible devices that are capable of withstanding significant strain. The interplay between semiconducting property and piezoelectricity leads to the emergence of unique device characteristics. One of the distinctive features of the piezoelectric oxide nanostructure is its reversibility; materials that show the direct piezoelectric effect when stress is applied also display the reverse piezoelectric effect (generate stress, when an electric field is applied) [55]. Zinc oxide (ZnO), lead zirconate titanate (Pb(Zr,Ti)O_3 or PZT), or barium titanate ($BaTiO_3$) have attracted significant attention due to their unique piezoelectric properties at the nanoscale [56, 57].

The extreme sensitivity to mechanical deformation of piezoelectric oxide nanostructures can create a substantial electric charge in response to modest quantities of applied stress, which is one of their key benefits. As a result, they are used in a variety of sensors and actuators, such as pressure sensors [59], acceleration sensors [60], and strain gauges [61] (see Fig. 5). In addition to their high sensitivity, piezoelectric oxide nanostructures also have high piezoelectric coefficient. Therefore, a larger electric charge can be generated in comparison to other piezoelectric materials, making them suitable for use in high-voltage applications [62].

Piezoelectric oxide nanostructures can be used in energy harvesting devices, such as piezoelectric generators [63], which can convert mechanical energy from sources such as vibrations or pressure changes into electrical energy. Piezoelectric oxide in microfiber morphologies offers a fascinating approach for converting mechanical energy into chemical energy through water splitting, a process known as piezoelectric catalysis [64]. This technology holds enormous potential for cutting-edge environmental remediation efforts, making it an area of great interest and excitement.

The strain-sensitive properties of piezoelectric materials have an impact on their performance in electrical devices. Few oxide-based piezoelectric devices have low

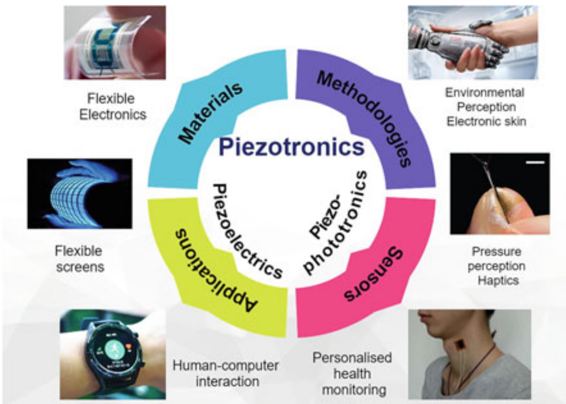

Fig. 5 Metal oxide nanostructures in piezotronics. Reprinted from Ref. [58], Copyright 2021, with permission from Elsevier

output voltage, which affects overall power generation. Some piezoelectric materials are also unstable at high temperatures or humidity, and the synthesis and processing of them can be costly, limiting their usage in specific applications. Therefore, further study is required to fully understand their potential and to create scalable and cost-effective ways for synthesizing and integrating them into practical applications.

4.4 Magnetic Oxide Nanostructures

In recent years, magnetic oxide nanostructures have gained considerable attention owing to their distinctive nanoscale properties (such as superparamagnetism, shape anisotropy, high magnetic moment, etc.) and potential applications in diverse fields like data storage [65] and sensing [66]. The emergence of state-of-the-art synthesis techniques like sputtering, electrodeposition, superconducting quantum interference device (SQUID), and lithography enables the production of oxide nanostructures in diverse shapes and sizes [67].

Traditional data storage technologies, such as hard disk drives, rely on the magnetic properties of materials to store and retrieve data. However, the size of these devices is limited by the minimum size of the magnetic domains that can be used to store data [69]. By using magnetic oxide nanostructures, it is possible to create smaller, and more efficient data storage devices.

Another potential application of magnetic oxide nanostructures is in drug delivery (see Fig. 6). These nanostructures may be tailored to certain cells or tissues in the body by functionalizing them with particular chemicals or medications. The effectiveness of drugs may be increased, and adverse effects may be decreased with this tailored distribution. In drug delivery systems, superparamagnetic iron oxide nanoparticles (SPIONs) are a key component and may be effective MFH agents (magnetic fluid hyperthermia) [70, 71].

Magnetic oxide nanostructures have a wide range of potential applications, however, there are challenges that must be overcome before their full potential can be realized. For instance, creating homogeneous, high-quality nanostructures is difficult. The characteristics of these materials at the nanoscale and how they might be modified for particular applications also need to be better understood.

4.5 Transparent Electronics

Transparent conductive oxide (TCO) nanostructures are ideal conductive materials that exhibit low electromagnetic wave absorption while maintaining high transparency across a broad range of the visible spectrum. These nanostructures are typically composed of materials such as indium tin oxide (ITO) [72], aluminum-doped zinc oxide (AZO) [73], or tin dioxide (SnO_2) [74]. Among them, ITO is widely used in transparent conductive nanostructures owing to its ability to be deposited in a thin

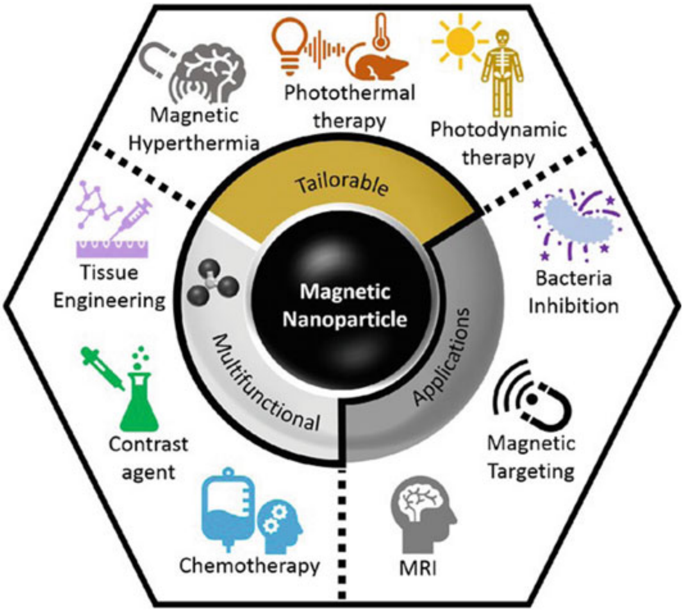

Fig. 6 Magnetic nanoparticles for various biomedical applications. Reprinted with permission from Ref. [68]. Copyright 2021 American Chemical Society

film, besides its electrical conductivity and transparency [72]. While ITO or AZO can be doped n-type, achieving p-type conductivity is very hard in these materials due to heavy hole masses. Thanks to the delafossites (ternary oxide $Cu_xA_yO_z$, which constitute Cu and any other one metal A) and mayenite cage structure type transparent conducting oxides, which typically show p-type semiconducting properties [76]. The ability to transmit a high percentage of visible light makes TCO nanostructures ideal for use in transparent electronic devices [77]. In addition, TCO nanostructures are cost-effective alternative to traditional transparent electrodes owing to their relatively easy fabrication [78]. The high transparency with extensive electrical conductivity makes them useful for various electronic devices, including touch screens [79], LED displays [80], solar cells [81], and smart windows [82]. TCO nanostructures are also being explored in flexible electronics and wearable devices [79] (see Fig. 7). However, TCO nanostructures are not as conductive as metals such as copper or silver, which can limit their use in specific applications. In addition, TCO nanostructures can be brittle and prone to cracking, affecting their long-term durability.

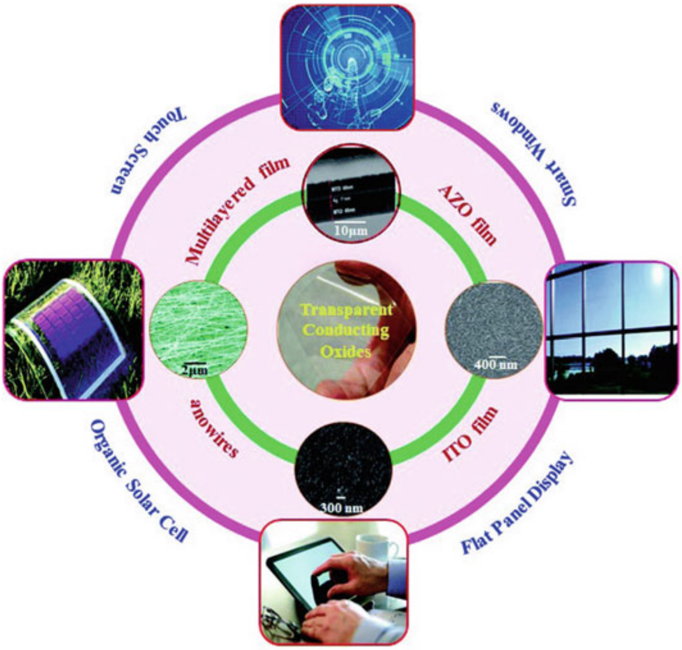

Fig. 7 Schematic representations of transparent conducting oxide nanostructures in modern electronic applications. Reproduced from Ref. [75] with permission from the Royal Society of Chemistry

4.6 Oxide Nanostructures as Photocatalyst

Heterogeneous photocatalysis offers the ability to directly transform solar energy into efficient chemical energy, thus providing environment-friendly solutions [83] (see Fig. 8). Due to the ability of charge carrier creation and separation in stimulated phase with adequate energy, oxide nanostructures are potential in electronics. Photocatalytic oxide nanostructures have an advantage in using visible light efficiently for photocatalysis, unlike most metal oxides that can only absorb ultraviolet (UV) light. By creating metal oxides in nanostructure form, their light absorption can be extended to the visible spectrum, enabling them to use more solar energy. In addition to their ability to absorb light, photocatalytic oxide nanostructures also have a large surface area, which allows them to catalyze chemical reactions efficiently. For example, in water purification applications, the large surface area of the nanostructures allows them to effectively remove contaminants from water by catalyzing their breakdown into harmless byproducts. The efficient photocatalyst should have an adequate bandgap with suitable morphology besides a large surface area. Transition metal-based oxide nanostructures like titanium dioxide (TiO_2) [85], zinc oxide (ZnO) [86], or tungsten oxide (WO_3) [87] have been widely studied for their potential

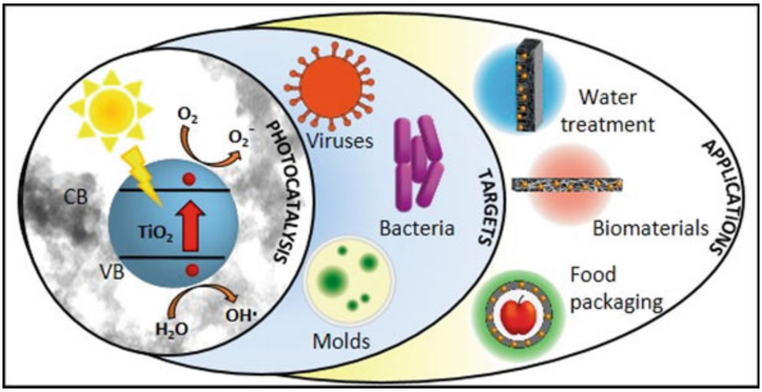

Fig. 8 Applications of photocatalytic TiO_2-based nanostructured materials. Reprinted with permission from Ref. [84], which is licensed under a Creative Commons Attribution 4.0 International License. Licensee MDPI, Basel, Switzerland © 2020

use in a variety of applications, including water purification, air pollution control, and energy conversion.

The stability of photocatalytic oxide nanostructures is a major challenge as they can degrade over time, and their synthesis is difficult as it requires precise control over their size and shape. Moreover, the presence of dopants and defects significantly affects the conductivity and charge carrier mobility in oxide nanostructured photocatalyst and hence the solar-to-hydrogen conversion efficiency. Changing the layer number [88], hetero-structuring [89], varying nanowire diameter [33], and introducing strain [90] in nanostructures are proposed as efficient strategies for engineering defect transition level and hence the device performance. However, oxide nanostructures are susceptible to persistent localized polarons and defects [91], which can have poor charge transport properties [92].

4.7 *Thermoelectric Oxide Nanostructures*

Thermoelectric (TE) materials have the ability to convert heat into electricity, or vice versa, to help overcome global warming and climate change issues with efficient energy utilization and suppression of CO_2 emissions from fossil fuels. Until now, bismuth chalcogenides (Bi_2Te_3, Bi_2Se_3) [94, 95] and lead telluride (PbTe, $PbTe_xSe_{1-x}$) [96] based nanostructured materials are widely used for waste heat recovery and temperature sensing due to their high electrical conductivity (σ) and Seebeck coefficient (S) with low thermal conductivity (κ) resulting in a higher figure of merit (ZT $= S^2\sigma T/\kappa$) for energy conversion. However, these materials are composed of toxic, naturally rare, heavy elements easily oxidizable in air, which restricts the deployment of thermoelectric materials for extensive applications. In contrast, thermoelectric oxide nanostructures are composed of nontoxic, naturally abundant, comparatively light, and cheap elements, thus having the potential for thermoelectric applications [97]. Spinel oxides [98], and oxychalcogenides [99] based oxide nanostructured are proposed as potential thermoelectric materials due to ultralow thermal conductivity and anharmonic phonon scattering.

In addition to their high ZT, thermoelectric oxide nanostructures have good stability and durability, making them suitable for long-term applications. Because of that, these materials are realized in thermoelectric generators [100] and solar thermal energy generation [51] (see Fig. 9). They are also compatible with a wide range of fabrication techniques, which allows them to be easily integrated into various devices.

Despite their potential, the low electrical conductivity of thermoelectric oxide nanostructures can limit their efficiency [101]. While p-type thermoelectric materials have been fabricated mostly Co-based oxides (Na_xCoO_2 [102] and $Ca_3Co_2O_5$ [103]), achieving n-type TE materials is still challenging [104]. Additionally, synthesizing thermoelectric oxide nanostructures is difficult, as it requires precise control over the size and shape of the nanostructures. Several design principles, such as rattling [105], chemical bond hierarchy [99], decoupling atomic contributions [98], and isovalent substitutions have been developed to achieve low thermal conductivity with high ZT. However, a manual search for potential TE with state-of-the-art theoretical and experimental techniques is time-consuming and resource-extensive. In this aspect, a high-throughput search of TE materials combined with machine learning [106, 107]

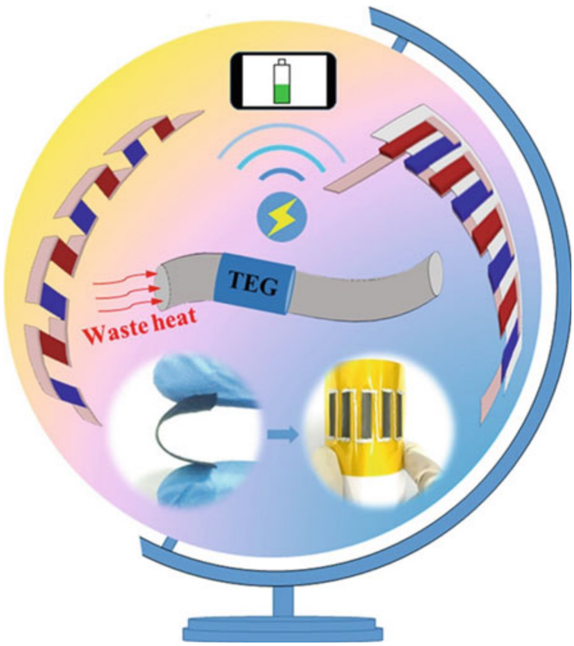

Fig. 9 Schematic depiction of thermoelectric generators (TEGs), which converts waste heat into electrical power. Reprinted with permission from Ref. [93], which is licensed under a Creative Commons Attribution 4.0 International License

has been demonstrated as an efficient approach for accelerated search of viable TE materials, including oxide-based nanostructured materials.

4.8 Oxygen-Deficient Metal Oxide Nanostructures

Metal oxide nanostructures are widely employed in a variety of applications, ranging from energy devices to bio-electronics, due to the benefits over ordinary nanostructures outlined in earlier sections. Although each metal oxide has its own restrictions for particular applications, generally, the low electrical conductivity of metal oxides has been a permanent barrier to their use as electrode materials [108]. As a consequence, oxygen-deficient nanostructures are a class of materials that has attracted substantial interest in recent years due to their ability to modify and fundamentally enhance their electrical characteristics by the controlled insertion of oxygen vacancies into metal oxides.

These nanostructures are highly reactive and have a high surface area, which is often several times larger than that of bulk materials making them suitable for various electronic applications [110] (see Fig. 10). In addition to their high surface area, oxygen-deficient metal oxide nanostructures also exhibit a range of other interesting properties. For example, they can show enhanced electrical conductivity, magnetic properties, and chemical stability compared to their bulk counterparts [111]. These properties make oxygen deficient metal oxide nanostructures attractive for use in energy storage and harvesting devices, gas sensors, catalysts, and fuel cells [2].

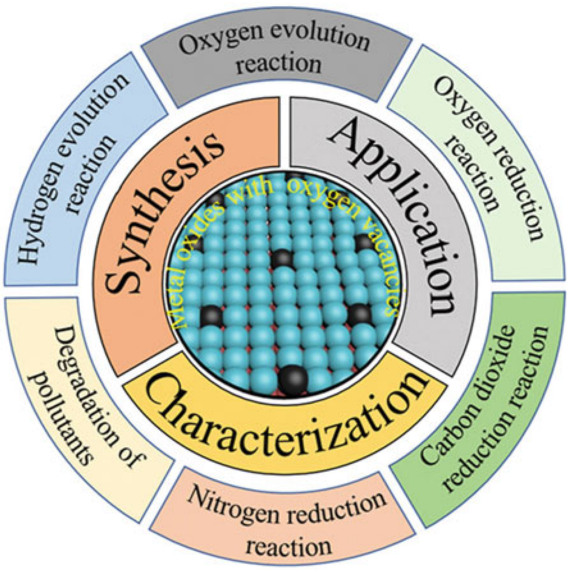

Fig. 10 Applications of oxygen-deficient metal oxide nanostructures semiconductors for energy and environmental catalysis. Reprinted from Ref. [109], Copyright 2021, with permission from Elsevier

One of the most widely studied oxygen-deficient metal oxide nanostructures is cerium dioxide (CeO_2), also known as cerium oxide or ceria. Ceria has a cubic crystal structure and is a good electrical conductor, making it useful in a variety of applications, such as catalysts [112] and gas sensors [113]. It is also a good oxygen storage material and can be used to remove pollutants from exhaust gases [114]. Another important oxygen-deficient metal oxide nanostructure is titanium dioxide (TiO_2), which has a variety of applications in areas such as photocatalysis, solar cells, and coatings [115]. Because of their superior pseudocapacitances, oxygen-deficient metal oxide nanostructures like as manganese oxide (MnO_2), cobalt oxide (Co_3O_4), and nickel oxide (NiO) have also been explored for supercapacitors [116].

Although oxygen-deficient metal oxide nanostructures have promising potential applications, their synthesis and investigation are ongoing areas of research that present many challenges. One of the primary obstacles is the difficulty in controlling the amount of oxygen deficiency in these materials, which can greatly affect their properties. Additionally, there is a need for additional research to comprehensively understand the mechanisms underlying their unique properties and to optimize their manufacturing and processing techniques.

5 Challenges

Metal oxides in nanoarchitecture and hierarchical structure have widespread applications in micro to nanoelectronics, as discussed in the preceding section. Here, we summarize several general challenges and limitations of using metal oxide nanostructures in electronics:

Synthesis and processing: Metal oxide nanostructures with desirable characteristics and in a reproducible manner can be difficult to synthesize and process. The most significant challenge is the cost-effective production of oxide nanostructures. High-quality defect-free nanomaterials are often created using specialized equipment and, under extreme circumstances, restricting their large-scale manufacture. Controlled production of nanomaterials remains a challenging task. More concentrated efforts are needed to create novel synthesis methods that overcome the difficulties associated with traditional methods.

Stability: The chemical composition and structure of the oxide, external variables (such as temperature, humidity, and pressure), and the existence of defects or impurities all influence the stability of oxide nanostructures. Oxide nanostructures with high crystalline perfection are often more stable than those with defects or impurities. This is due to the fact that defects or impurities can serve as nucleation sites for structural alterations or degradation, resulting in the creation of unstable phases or the disintegration of the oxide. External circumstances can potentially affect the stability of oxide nanostructures. High temperatures can cause new phases to develop or the oxide to decompose. In the same way, the presence of moisture or other contaminants can cause instability. Overall, the stability of oxide nanostructures is a complicated and multidimensional topic, and the stability of each single oxide nanostructure will rely on its specific circumstances and features.

Conductivity: Majority of oxide nanostructures have poor conductivity. Due to the high surface-to-volume ratio of nanostructures, surface atoms can behave as scattering centers, obstructing electron pathways and reducing the conductivity of the material. The conductivity of oxide nanostructures is further hindered by impurities and the quantum size effect. Therefore, a future research objective should be to discover strategies to improve the conductivity by lowering the scattering centers.

Compatibility with existing technology: The successful integration of oxide nanostructures in electrical devices is one of the most complex challenges in oxide nanostructure research. It has been shown that nanostructure doping, contact resistance, and surface passivation are plausible approaches to achieving accurate and repeatable positioning of those nanostructures. Despite significant progress in these fields, a comprehensive strategy that addresses all of these challenges at once and builds a solid technical foundation for oxide nanostructure integration is still lacking, at least not in a fashion that is consistent with low-cost and large-area processing.

Toxicity: Some metal oxide nanostructures, like those containing certain transition metals (like Co-based), can be toxic to humans and the environment, which can be a concern when using these materials in electronic devices. Potential risks might arise from oxide nanostructure bio-accumulation. The toxic effects of metal oxide nanostructures can be facilitated by a number of factors, including exposure, size, dissolution, etc. As a result, future research should concentrate on reducing oxide nanostructures' toxicity before incorporating them into electronic systems.

Limited fundamental understanding: The importance of oxide nanostructures in electronic applications is growing at a rapid pace because of various advantages. However, there is still a limited fundamental understanding of the exotic properties and behavior of metal oxide nanostructures, which can make it challenging to design and optimize their use in electronics.

Therefore, by combining advanced experimental techniques, theoretical analysis, and data-driven approaches that span from understanding at the atomic level to device fabrication, we can achieve the long-term goal of creating diverse and multi-functional electronics that are also sustainable.

6 Future of Electronics: CMOS Technology and Beyond

The shrinking of devices owing to advancements in silicon lithography makes the future of electronics exciting yet challenging. While transistors approach closer to the atomic scale and production prices rise, the need for alternate methods has become more essential. Investment in computer architecture and fundamental sciences, such as materials science, is necessary in this circumstance to investigate potential replacement materials and alternative device physics to enable continuous technological advancement.

Metal oxide nanostructures have demonstrated great potential in various electronic applications, as discussed in Sect. 4. In transparent electronics, several metal oxide in nanostructure morphology can serve as a replacement for expensive and fragile indium tin oxide as transparent conductive materials. MO nanostructures have also proven to be useful in energy storage applications, such as lithium-ion batteries and supercapacitors, owing to high specific capacitance and good cycling stability. Due to their great sensitivity, selectivity, and rapid response time, MO nanowires have been employed in sensing applications such as gas sensors, biosensors, and environmental sensors. The interplay of electronic and thermal properties makes them promising for thermoelectric applications, which can be tuned by controlling their size, shape, and doping. MO nanostructures have a bright future in various fields, and their potential for commercial applications is vast. Further research and development in this area will undoubtedly lead to the development of novel materials and devices with improved performance and functionality.

The current complementary metal oxide semiconductor (CMOS) technology has been the backbone of the electronics industry for several decades. By combining p-type and n-type MOS transistors on a single integrated circuit, CMOS technology has effectively resolved the drawbacks associated with the use of separate p-MOS and n-MOS circuits. This innovative approach allows for more versatile circuit designs and significantly reduces circuit noise and complexity, making it an attractive option for a wide range of electronic applications. With CMOS, high-performance circuits can be developed, that are not only efficient but also highly reliable and cost-effective. CMOS has undergone significant advancements over the years to increase the density of transistors on a single chip, which has led to the development of more powerful and efficient processors and other digital devices. However, to overcome the challenges of data movement costs and other limitations, new computing architectures and advanced packaging technologies, such as monolithic three-dimensional integration and photonic co-packaging, are being explored. The development of FinFET technology is also seen as a viable option for continuing to scale CMOS beyond its current limits.

Looking beyond CMOS, there are three axial-pathways that can shape the future of electronics (depicted in Fig. 11). The first axial-pathway involves the exploration of new materials and devices such as carbon nanotubes, graphene, and other two-dimensional materials that have unique electronic properties and have the potential to outperform traditional materials like silicon. The second axial-pathway is focused on developing a new model of computation, such as quantum computing, which has the potential to solve problems beyond the capability of classical computing. Moreover, neuromorphic computing emulates the structure and function of the human brain, leading to more energy-efficient devices that can perform complex tasks with greater accuracy. Further, artificial intelligence-driven machine learning and deep learning along with the Internet of Things (IoT) are developing with great promises for the advancement of future electronics. The third axial pathway focuses on creating more energy-efficient and re-configurable architectures, such as the development of system-on-chip with 3D stacking. In the search for a CMOS replacement, the scalable development of new transistors is a crucial area of research. Promising candidates

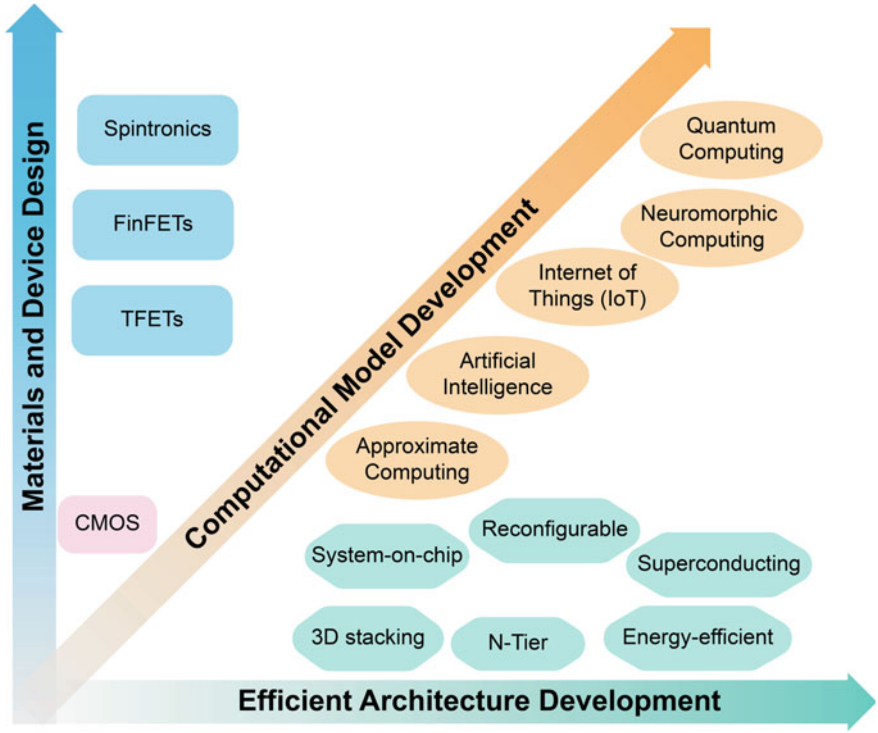

Fig. 11 Three promising avenues for development and progression of future electronic technologies

such as tunnel field-effect transistors, spintronic devices, and nanoelectromechanical systems (NEMS) are being explored to push the limits of electronics beyond what is currently possible.

The future of electronics is bright, with many exciting developments on the horizon. By investing in architecture and the exploration of the three axial pathways, we can push the boundaries of what is possible in electronics and continue to develop smaller, more powerful, and energy-efficient devices that will transform our lives in numerous ways.

7 Conclusions

In summary, this chapter provides an overview of metal-oxide nanostructures, including their synthesis, characterization, and potential applications in modern electronic devices. It highlights the benefits of using MO nanostructures over traditional nanostructures while acknowledging the challenges that still need to be overcome. The chapter also discusses three pathways based on future research goals in the field, such as improving the properties and performance of oxide nanostructures, developing new synthesis and characterization techniques along with efficient architecture development. Overall, the chapter emphasized the importance of metal-oxide nanostructures in progressing the future of electronic applications.

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