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CHARACTERISTICS AND PROPERTIES OF NANO-METAL OXIDE: A REVIEW

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Abstract: Nano-metal oxides have attracted significant attention in recent years due to their unique physical, chemical, and structural characteristics that differ greatly from their bulk counterparts. These nanomaterials exhibit enhanced surface area, improved thermal stability, tunable electronic properties, and remarkable optical and catalytic behavior. This review presents a comprehensive overview of the characteristics and properties of nano-metal oxides, including their structural, optical, electrical, magnetic, and chemical properties. The synthesis methods, size-dependent behavior, surface modifications, and their influence on performance in various applications such as catalysis, environmental remediation, energy storage, sensors, and biomedical fields are also discussed. The paper aims to provide a clear understanding of structure–property relationships in nano-metal oxides and highlights current challenges and future research directions in this rapidly growing field.

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Introduction

Nanoscience and nanotechnology have remarkably attracted the interest of the scientific community due to their outstanding outcomes in various fields, such as sensors, optoelectronics, electronics, catalysts, and so on. The word 'nanoscience' is about the study of matter particles and structure on the nanometre scale. Generally, nanoscience covers a broad area such as material science, physical science, chemical science, and engineering. The Nanoparticles are very well-established in the scientific literature. It became the smallest controlled ordinary object, which is further characterized by Newton's law of motion, but these nanoparticles became bigger than ordinary atoms or molecules that were further studied by quantum mechanics. Nanoparticles have various fundamental properties from larger particles, like particles having grain sizes larger than 0.5 µm, to well-dispersed nanoparticles. Spheroid-like nanoparticles were studied with a well-ordered arrangement of atoms, showing nano-crystalline particles. The execution of nanomaterials, such as size, shape, and textural parameters of the particles, and for the suitability of the materials. Nanotechnology has become the appropriate, fastest-growing technology in favor of mankind. Nanotechnologies range from 1 to 100 nm of nanoparticles for the fabrication of nanostructures, and nanoparticles are the basic components [1]. These 'Quantum dots' or 'Artificial atoms' are nanoparticles having very appropriate electronic energy levels, and they also have the compositions of semiconductor materials. In the last two decades, researchers have known that the matter level of single atoms and groups of atoms characterizes the properties of materials and systems at the nanoscale level. Their capability has led to the astonishing discovery of small no.'s of atoms or molecules in nanoscale clusters that have shown properties like strength, conductivity, resistivity, absorption, etc. that are different from other properties of the same matter, either on the single molecular scale or bulk scale. Nanoparticles are composed of three layers: surface layers, shell layer, and core layer. Their surface layer is the function of small molecules, polymers, and metal ions. The shell layer is different for different materials, and the core layer is the central portion of nanoparticles.

Classification of nanoparticles

Nanoparticles are classified into various types, such as carbon-based nanoparticles, metal nanoparticles, ceramic nanoparticles, semiconductor nanoparticles, polymer nanoparticles, and lipid nanoparticles.

Carbon-based nanoparticles

Fullerenes and carbon nanotubes (CNTs) represent two major classes of carbon-based nanoparticles. Fullerene contains nanomaterials that are made of a globular hollow cage, such as allotropic forms of carbon. They contain various properties like electrical conductivity, high strength, structure, electron affinity, and versatility [2-3].

These materials have various structures, like pentagonal and hexagonal carbon units. Where their hybridization is sp2. While others are fullerene, consisting of C60 and C70.

Metal nanoparticles

These types of nanoparticles were made by metal precursors. These nanoparticles possess optoelectrical properties named LSPR (Localized Surface Plasmon

Resonance) characteristics. Nanoparticles like Cu, Ag, and Au, which are alkali and noble metals, show a broad absorption band in the visible region of the electromagnetic solar spectrum. In the present day, cutting-edge materials, therefore, shape, face, and size are shown by controlled synthesis of metal nanoparticles by Dereaden et al. [4]. They are used in various research studies due to their advanced optical properties. Coating of gold nanoparticles is used for SEM sampling, an electronic stream that helps to increase its high quality, so SEM images show a clear vision.

Ceramic nanoparticles

They are synthesized by heat and successive cooling, so these nanoparticles are also known as inorganic non-metallic solids. They form in various forms, like amorphous, polycrystalline, dense, porous, and hollow forms [5]. These nanoparticles are more appropriately used in a large number of applications, like photocatalytic, photo-degradation of dyes, and imaging applications.

Semiconductors nanoparticles

These are the most appropriate nanoparticles among all due to the properties that lie between metals and nonmetals [6]. These semiconductor nanoparticles show optical properties like wide band gaps and show significant changes in their properties. So, due to their better optical behaviour, they are used in various applications like photocatalytic and opto-electronics devices [7].

This type of nanoparticle shows better bandgap and band edge position, so they are used in water splitting applications [8]

Polymer nanoparticles

The polymer nanoparticles (PNP) are organic-based. Their shape is nano-spherical. Their spherical shape is used for the adsorption of molecules at the outer boundary of nanoparticles, which is completely encapsulated within the particles [9]. The PNP nanoparticles are further used for various applications.

Lipid-based nanoparticles

Lipid-based nanoparticles are used on a large scale in biomedical science. They also work as polymer nanoparticles and are spherical. Their size varied from 10 to 100 nm. This type of nanoparticle works in various applications like drug carriers, delivery, and RNA release in cancer therapy [10]. A wide variety of nanoparticles are used as a solid core that is made of lipid and contains lipophilic molecules. So, basically, they are used in a wide range of medical sciences.

Nanomaterials have at least one dimension in the range 1-100 nm. The materials can be zero-dimensional (0D) to two-dimensional (2D), with three-dimensional (3D) being considered as bulk. The range of morphologies has also been observed [11], as shown in the figure. 1.1. 0D Quantum dots are controlled by the quantum effect. These include both their photoelectric and electric properties.

Some of the properties are as follows-

1. The bandgap can be tuned by changing the size of the material.
2. The thermal properties of the material can be changed greatly, such as the melting point.
3. The radiative lifetime ranges from tens of picoseconds.

Whereas zero-dimensional contains nanoparticles which tend to be spherical, one-dimensional contains nanorods and nanowires, and two-dimensional contains quantum wells and thin films.

Nanoparticles as a semiconductor

Nanoparticles are used as semiconductors due to their properties being different from the vast bulk of semiconductors. At first, Ostwald said “the world of neglected dimensions” [12]. Due to the different packing of electrons, which have a range of energies and are found at different energy levels, those molecules can contain an infinite number of energy levels. These energy levels contain a valence band and conduction bands, which further differentiate between forbidden energy. It is known as an energy gap or band gap. These semiconductors contain a bandgap in the range of 0.3-3.8 eV [13]. As the number of atoms increases, it does not affect energy levels. The atoms were so close, and they can be described as continuous, so no changes appear in the addition of atoms. There are two fundamental factors of nanocrystalline semiconductors. These are high surface-to-volume ratios and the electrical and physical properties that determine the actual size of particles [14]. The Bohr radius is different for different materials, and the bandgap is smaller than the Bohr radius, depending on size. When the size of particles decreases, the band gap increases. The size of the bandgap is affected by the dimension of the particle. The energy difference between the valence and conduction bands increases as the dimension of the material decreases from 3D to 0D for the electron and the hole. The Schrodinger wave equation can solve both 1D, 2D, 3D, and spatial dimensions of the Bohr radius of the electron, hole, or e-h pair, similar to the quantum mechanics ‘particle in a box’ theory [15]. Semiconductors are of two types. These are direct and indirect semiconductors. For example, ZnS, CdSe, GaAs, and InAs belong to the II-IV group. ZnS contains a direct bandgap, whereas Ge, Si, and GaP contain an indirect bandgap. The conduction band directly lies above the valence band in the case of a direct bandgap. Electrons maintain their momentum and are placed in the conduction band, and directly combine with the holes in the valence band in the form of a photon. The energy will be emitted when the electron returns to the conduction band. This emission is known as spontaneous emission and directly has optical energy, and the absorption coefficient is large. Examples of direct bandgap are gallium arsenide. An equation shows the relation between the absorption coefficient and energy of photon-$(\alpha h\upsilon)^{1/n}=A(h\upsilon-Eg)$. Where ‘$\alpha$’ is the absorption coefficient, ‘h’ is Planck’s constant, ‘A’ is the absorption coefficient, Eg is the energy bandgap, ‘υ’ is the frequency of transition, ‘n’=1/2 for direct transition, and ‘n’=2 for indirect transition. Whereas indirect similarity shows not a direct transition of an electron across the bandgap between the conduction band and the valence band, it is known as a forbidden transition. Electrons alone cannot overcome the gap between the conduction band and the valence band. It requires more momentum, so a third body can be introduced to overcome this effect, known as phonon or crystallographic defects. So, the electron reacts to a non-radiative recombination site, and the electron comes back to the valence band at radiative recombination. So, indirectly, they are ineffective at emitting light and have small absorption coefficients on Si. As the temperature increases, the conductivity of the semiconductor increases, and electrons have more energy that is excited to the conduction band as the electron moves from the valence band to the conduction band, leaving a hole in the valence band. So, there is an equal number of electrons in the conduction band and an equal number of holes in the valence band. An Intrinsic and extrinsic semiconductor is one whose conductivity depends on electrons. Intrinsic semiconductors possess no defects and are known as pure semiconductors. Intrinsic semiconductors are formed from extrinsic semiconductors by doping and have unequal e-h concentrations. This doping in an intrinsic semiconductor may form an extrinsic semiconductor. This impurity changes the properties of the semiconductor properties where electrical properties are changed through doping in the intrinsic semiconductor. There are two types of doped semiconductors, namely n-type and p-type. The N-type semiconductor contains pentavalent, an impurity, which means the extra electron in the conduction band electrons may increase conductivity. Due to extra electrons excited to the conduction band and the electrical conductivity examples like arsenic, antimony, and phosphorus. Whereas the p-type semiconductor is a trivalent impurity due to it possessing an extra hole and lacking an electron. Boron, aluminium, gallium, and hence holes are freely moved, which increases conductivity.

Literature review

Mahadi et al. [16] reported that CdO thin films have been synthesized by a simple chemical method. Their various properties were examined, and CdO has a cubic crystal structure. CdO samples were characterized by various techniques; the structural, morphological, and various other techniques were used to fabricate their crystal structure, crystallite size, bandgap, and their electrical conductivity [17]. Zinc oxide (ZnO) contains a bandgap of 3.37eV and has a very high exciton binding energy of 60 meV. It is fabricated by the sol-gel method. The metal oxide semiconductors were prepared by numerous methods. After preparation, their numerous properties were calculated and further used for various applications [18-21]. Their properties were increased when doped with rare earth metals. The most commonly used rare earth metals are Y and Ce. Maramiet al. [22] prepared TiO_2 and Ce-doped TiO_2 from the sol-gel method with various doping percentages, and dopants to improve their various properties. The structural and morphological properties of pure and Ce-doped ZnO were investigated. Ce doping improves the crystallinity of pure ZnO.Ahmed et al. [23] reveal that the Ce, Mn, and Al doped and undoped ZnO thin films were fabricated by the sol-gel method, investigated their various properties like structural, optical, morphological, and photoluminescence properties, and examined the intensity of the UV and the visible emission peak decrease after doping of Ce and Al. Their UV-spectroscopy measurements decrease in optical bandgap as compared to undoped ZnO thin films.Yttrium-doped ZnO was synthesized by a co-precipitation method. The X-ray diffraction confirms the hexagonal wurtzite structure with crystallite sizes of 16 and 30 nm [24]. Their optical band gap decreases with increasing Y concentration in ZnO. In the last decade, various nanocomposites such as CdO-ZnO, CdS-ZnS, ZnO-MgO, ZrO_2-Y_2O_3, SnO_2-TiO_2, and CdSe-CdS have been demonstrated and show very good stable transport properties and lead different electronic devices [25-30]. Metal oxide gas sensors were used to detect gases like LPG, CO_2, and O_2 etc. [31-33]. Zhao et al. [34] demonstrated the ethanol gas sensing mechanism for the material CdO/ZnO. The role of CdO on the photocatalytic activity of electrospun ZnO nanofibers [35]. Miller et al. [36] reviewed the gas-sensing properties of the different structures. The Co, Cu doped ZnO showed the gas sensing properties [37]. Kartik et al. [38] have shown the synthesis of CdO-ZnO nanocomposite for the antibacterial activity against human pathogens. The synthesis of ZnO: CdO nanocomposite by SILAR techniques and examined for gas sensing properties [39]. Various materials have been examined for metal oxide sensors for both single and multicomponent oxides that have been published in various reviewed articles [40-43]. The metal oxide gas sensors have been reported for gas sensing of ammonia, methane, and chlorine [44]. The metal oxides like iron oxide, molybdenum trioxide, and niobium are reported for various gas sensing applications [45-47]. The gas sensing application for the CdO metal oxides has been reviewed in that article [48]. The metal oxides such as V_2O_5, TiO_2, and WO_3, etc, have been reported by different researchers for different gases [49-51]. Kumar et al. [52] examined the structural, morphological, optical, and other properties of ZnO and CdO doped ZnO by the PLD method. Ghosh et al. reported an LPG gas sensing application for the zinc oxide thin film [53].Joshi et al. [54] review a chemiresistive room temperature gas sensor sensing gases like NO_2, NH_3, H_2, SO_2, CO, etc., including features like selectivity and high response sensing. Sohny et al. [55] fabricated doped and undoped ZnO thin films for CO_2 gas sensing applications. The films were prepared by spray pyrolysis with different concentrations of Mn. Their structural property revealed the wurtzite structure. As the temperature increases, their sensitivity decreases for the O_2, CO_2 sensing mechanism for Mn-doped semiconductor [56]. A sensor O_2, CO_2-based, was operating at a temperature lower than 70 °C. Habib et al. [57] prepared ZnO-like morphology as nanowires by using sol-gel methods. CO_2 gas sensors were fabricated with good sensitivity. They are along with response and recovery time at a temperature of 200 °C. CO_2-based gas sensors were fabricated. The effect of temperature on the sensor response, and observing that the temperature variation of sensor response is nonlinear, and therefore temperature can be used as one of the independent Parameters. There were various sensors that were fabricated for the different gas sensing applications and reported different sensor responses and recovery time along with different gases such as O_2, N_2, CO_2, ammonia, etc. Mani et al. [58] investigated a high ammonia sensor at room temperature using a spray deposition method of zinc oxide thin films. The better sensor responses were observed for undoped ZnO thin film; their selectivity, stability, and reproducibility were also examined and found to be better results. ZnO thin films fabricated by spray pyrolysis and atomic layer deposition techniques, and their sensing application at room temperature, were studied [59-60]. Onkar et al. [61] said that ZnO contains a wurtzite structure, its morphology is a rod, a tube-shaped morphology, and the electrical properties revealed an ohmic nature. The prepared ZnO is further used for the gas sensing applications of LPG, NH_3, and CO_2 gas sensors. The results of sensing were detected as poor, so doping is mandatory for improving the results of ZnO thick films and, therefore, improving gas sensing response. Tanvir et al. [62] reported gas sensing behaviour of copper oxide nanoparticles. The mechanism of CO_2 gas sensing is studied by FTIR spectroscopy and further explained by thermodynamic calculations. CdO samples were prepared by various methods. After their preparation, they were further used for various applications like gas sensing and photocatalytic applications [63].Sanoop et al. synthesize yttrium-doped ZnO for the photocatalytic degradation of methylene blue degradation of dyes. The photocatalytic degradation of Y-doped ZnO has been examined for the oxidation of methylene blue solution. Upadhyaya et al. [64] reported the ZnO: TiO_2 under visible light irradiation. The nanocomposites of the ZnO: TiO_2 enhanced the photocatalytic degradation of the methylene blue methyl orange(MB/MO) dye. The photodegradation was increased from 75 to 90 %, and the composition is 2:3 of ZnO: TiO_2 under visible light irradiation. The nanocomposites of the ZnO: TiO_2 and the photocatalytic degradation of pentachlorophenol [65]. Zulfikar et al. [66] proposed the idea that the degradation of humic acid by the composite of TiO_2:ZnO from the aqueous solution showed better photocatalytic activity, as the loading dose and the intensity of light increased, it increased the photocatalytic degradation increased. Karidas et al. [67] revealed the cerium-doped zinc oxide for the degradation of methylene blue; the structural and morphological properties have examined the hexagonal structure of ZnO were examined. The doped and undoped ZnO have photodegradation efficiency that is 81% and 92% of methylene blue under visible light irradiation. Ong et al. [68] reviewed an article on ZnO for the photocatalytic degradation at visible light irradiation due to its low cost, non-toxic nature, and it is efficiency in the absorption of the solar spectrum as compared to TiO_2. Mikaeli et al. [69] revealed the pure and doped TiO_2 synthesis by spray pyrolysis, examined spherical morphology, and the bandgap varying from 2.4 eV to 3 eV, revealing the better photocatalytic response of the visible light irradiation. Results indicate that the Ce-doped TiO_2 shows better photocatalytic degradation than undoped TiO_2. The hexagonal structure of ZnO and the tetragonal structure of TiO_2 are from the structural properties, whereas the photocatalytic degradation of the composite nanorods under UV light irradiation for the rhodamine B degradation, their irradiation time is 90 min for the composite of ZnO: TiO_2. Ahmed et al. [70] examined nanocomposite powders of zinc oxide and titanium oxide, which were chosen due to their better photocatalytic activity.Faisal et al. [71] revealed that the Ce-doped ZnO nanorods like a morphology for the photocatalytic degradation. Ce-doped nanoparticles performed better photocatalytic performance than pure ZnO nanoparticles. Habib et al. [72] exhibit rare-earth-doped ZnO nanoparticles in the methylene blue dye degradation. Ce doping enhances better photocatalytic degradation than pure ZnO. Yan et al. [73] proposed the idea that the preparation and properties of Ce-doped TiO_2photocatalyst have a higher degradation rate of samples with 90% efficiencies, prepared by the sol-gel method. The doping of Ce decreases the recombination of photogenerated electron-hole pairs and captures the photo-holes. Therefore, Ce doping exhibits better photocatalytic activity.Zhang et al. [74] demonstrated that TiO_2 nanoparticles degrade various types of pharmaceuticals under sunlight irradiation. The prepared sample becomes a treatment of propanol in tap water, surface water, and wastewater effluent. It is further useful for the degradation of pharmaceuticals in both drinking water and wastewater treatment.

ZnO and its properties

ZnO is an attractive material for shorter wavelength, optoelectronic applications, owing to its wide band gap of 3.37 eV, larger band strength, and large exciton binding energy at room temperature. As a wide band gap material. Due to its non-Centro symmetric crystallographic phase [75], ZnO has piezoelectric properties [76], which are highly useful for the fabrication of devices. Such as electromagnetic coupled sensors and actuators. ZnO shows a wurtzite crystal structure. This wurtzite structure contains two interpenetrating hexagonal closed-packed sub-lattices, both consisting of one type of atom, either Zn or O atom, that are displaced by each other along their three-fold c-axis. It simply contains several alternating planes that are stacked layer by layer along a c-axis direction and tetrahedrally coordinated. Each anion at the corners is surrounded by four cations in the wurtzite hexagonal structure of ZnO. This represents the tetrahedral coordination and includes sp3 covalent bonding. ZnO shows a large number of applications. ZnO nanostructures contain nanoparticles, nanorods [77], nanowires, nanotubes, etc., and various morphologies. ZnO nanoparticles are formed by many methods, like sol-gel methods, hydrothermal, pulsed laser deposition [78], spray pyrolysis [79], and RF-sputtering [80]. The Sol-gel method has a low-cost, eco-friendly synthetic route. The ZnO nanoparticles are synthesized in a solution that requires a well-defined shape and size of ZnO nanoparticles. The basic principle of making ZnO was based on the decomposition of organometallic precursors and on the oxidized materials in air. Lattice parameters play an important role in making semiconductor devices [81]. There are four faces to determine lattice parameters, that are, free-electron concentration, defects, and impurity concentration, also the difference between and ionic radii of these two external strains. Due to these imperfections or defects, they have various influences on their electrical, optical, mechanical, and thermal properties [82]. Lattice parameters are measured by XRD. The a' and 'c' lattice parameters of ZnO can be calculated by their c/a ratio, wurtzite crystal structure is measured by XRD [83].

Electrical property

As a direct and wide band gap semiconductor having a large exciton binding energy (60 meV), that's why ZnO attracts the attention of researchers of optoelectronic and electronic devices [84].

In low and high electric fields, the performance of the transportation of electrons is different. The energy distribution of electrons in ZnO is unaffected at low electric fields because electrons cannot get much energy from applied electrical fields as compared to thermal energy. The electron mobility is constant because the scattering rate determines the electron mobility when an increment in the electric field is applied. From the applied electric field, the energy of electrons is equal to the thermal energy of electrons [85]. From its equilibrium value, the electron distribution function changes. Their temperature is higher than the lattice temperature. The mobility of ZnO depends on its growth process, film thickness, dopants, etc. The non-stoichiometric surface of the sample shows higher conductivity. Where carrier mobility is for ZnO 120-440 $cm^2v^{-1}s^{-1}$ at room temperature, and for electrons and holes, their mobility is found at 200 $cm^2v^{-1}s^{-1}$ and 5-50 $cm^2v^{-1}s^{-1}$ [86-87]. The effective mass of electrons and holes is $0.24m_o$ and $0.59m_{o,}$ respectively. So, electrons have higher mobility than holes [88].

Optical property

The optical properties of the semiconductors are calculated by both intrinsic and extrinsic effects. As we know, ZnO is a direct band gap semiconductor and a transparent conductive material [89]. Optical measurements were carried out by various techniques like optical absorption, transmission, reflection, spectroscopic, ellipsometry, photoluminescence, cathodoluminescence, calorimetric spectroscopy, etc. intrinsic transition between electrons in the conduction band, and holes in the valence band. Extrinsic properties due to dopants on defects that create discrete electronic states in the band gap and hence influence both absorption and emission processes. ZnO is a transparent conductive oxide; the optical bandgap of ZnO is 3.0-3.2 eV, a direct bandgap, and a wide bandgap near the UV region. The ZnO sample absorbed maximum light near 300-250 nm and possessed almost 90% light in the visible region. Due to the conduction of valence band transition, the luminescence of ZnO is observed near the UV region, and due to the defect level, the intermediate emission photons were also recorded. The ZnO samples show various advantages, like a wide bandgap, large breakdown voltage, high temperature, and high power operation. In n-type ZnO, the majority of charge carriers are due to their point defects, whereas p-type ZnO observed trivalent impurity by doping like 'Al' [90,91]. The main role of point defects and the incorporation of impurities used to control the conductivity in ZnO has resolved the main issues. ZnO contains group II-VI, which is insoluble in water but dissolves in many acids [92]. Due to its non-toxic nature, it is used in various applications, like the ceramic industry, medicine, food additives, etc., due to its adsorption/absorption reaction with oxygen ions. It is further used for gas sensing applications [93,94]. It contains various mechanical properties like Young's modulus, hardness, stiffness, and piezoelectric constant [95]. Their hardness is 4.5 on the Mohs scale, which is relatively soft, and their density is around 5.606g/cm^3. The other mechanical parameters are elasticity, stress, and strain, which involve morphological properties. It has high thermal conductivity, and this property makes it useful in additives, like it to rubber to increase the thermal conductivity of tires [96]. Their various properties are- Melting point-1975, Molar entropy-45.9 Jk^{-1}, Molar enthalpy-348kJ/mol.

CdO and its properties

CdO is a binary composition of the II-VI group semiconductors like ZnO. It has a growing area for research because of its own properties, like physical, optical, electrical, and chemical [97-98]. When nanoparticles of CdO show zero dimensions, it is very important for various applications due to the enhanced surface-to-volume ratio. Therefore, feasible changes are observed in the optical property. The optical property is directly involved with grain size. CdO is an n-type semiconductor that contains a crystallite rock salt structure (FCC), and the optical band gap is about 2.2 eV. CdO is a very promising transparent conductive oxide (TCO). CdO transparency in the visible region is less than ZnO. That's why it is used as a transparent conductive oxide. It has attracted a lot of attention due to its high conductivity and low resistivity [99-101]. The colour of CdO is seen as red-brown [102]. The amorphous CdO powder has been reported [102]. CdO is used for various purposes, like catalysts, cadmium plating bath, phosphorus, cadmium salts, etc [103]. The detailed structural, optical, electrical, and thermal properties are discussed. CdO is found basically in two crystal phases: rock salt and a cubic structure with face-centered. The Cadmium oxide cubic crystal lattice contains octahedral cations and anion centers. It contains different research group areas because it has various applications like solar cells, phototransistors, liquid crystal displays, gas sensors, and other optoelectronic devices [104]. The luminescence property is affected by the donor defects that arise from non-stoichiometry in cubic lattices of CdO [105]. Undoped CdO has a very high refractive index (2.49) [106]. It transmits 70-80% of light in visible regions, and its thickness varies with the grain size of CdO. The optical direct band gap is 2.1 – 2.2 eV, and the indirect band gap is 1.9 eV [107]. The band edge transmittance spectra are observed between 550-600 nm. That corresponds to the optical band gap energy. It shows high reflectivity in the IR region, and this behaviour is useful as a heat reflector [108]. In the luminescence spectrum, the visible photons are expected by direct transition from the conduction band to a valence band. Due to moderate electron mobility and high carrier concentration, CdO has high electrical conductivity. It has high electrical conductivity, which plays an important role in gas sensing devices. The conduction band is of 5s atomic structure. The resistivity and mobility of CdO were reported as 2.3 to 6.2 cm^3/Vs, increasing with an increase in temperature above 100K. As the temperature increased, their resistivity decreased from 3.310-3 to 1.410-3 ohm-cm [69]. CdO is a very hazardous material; its molar mass is 128.41 g/mol. The band structure is shown below-[109]. The solubility is 4.8mg/L, but soluble in dilute acid. Due to the toxicity of cadmium, it is a very hazardous material. The adsorption/absorption reaction with O_2 ions CdO is suitable for gas sensing applications. It is a very soft material with a density of 8.15 g/cm^3, which is much more than ZnO. The stress/strain in the thin film depends on the crystal lattice. It decomposes in an amorphous form with a very high melting point, which is 900-1000 °C. It has been prepared by various methods like chemical bath deposition (CBD), pulsed laser deposition (PLD), sol-gel, magnetron-sputtering, metal organic chemical vapor deposition (MOCVD), etc. It has other properties shown in Table [110]. Specific heat capacity- 43.64 J/mol-K, Molar enthalpy- 55J/mol-K, Enthalpy-258KJ/mol, Gibbs free energy-229.3KJ/mol.

TiO_2 and its properties

TiO_2 has various features like low resistivity, luster, cheap availability, and a lower bandgap. That's why it is used in various things like paints, toothpaste, cement, golf clubs, sunscreen, etc. It behaves like an n-type semiconductor, and, due to some defects, the metal oxide TiO_2 plays an important role in various chemical and physical applications. Because of the effect of doping, the conductivity changes from n-type to p-type. TiO_2 shows anatase, rutile, and brookite crystal structures [111]. The bandgap is an indirect bandgap that is 3.2 eV, and a direct bandgap is 3.25 eV, respectively [112-114]. This shows the more effective ways of photocatalytic application than rutile and brookite. Due to the representation rate of the recombination of electron-hole pairs, the anatase phase is the most dominant for photocatalytic applications. Due to the large surface area, the anatase phase has a large surface and shows more catalytic reactions than other phases [115]. The higher photocatalytic reaction is observed due to the higher surface area; the anatase phase shows a better response in the catalytic application [116]. TiO_2 shows a large excitation binding energy, is non-toxic, low-cost, has better synthesis, and is easily available. TiO_2 shows different metal binary compositions like ZnO/TiO_2. To increase the property of TiO_2, add the appropriate amount of O_2, Fe_2O_3, SiO_2, In_2, Al_2O_3 and ZrO_3. Titanium dioxide (TiO_2) has three polymorphs, namely anatase, rutile, and brookite, which influence the sensing properties. The anatase phase is preferred over rutile in gas sensing due to its higher photocatalytic activity. Anatase and brookite are thermodynamically metastable forms of (TiO_2), which irreversibly convert to rutile at high temperatures. This anatase-to-rutile transition has a severe effect on the sensor's sensitivity. Titanium dioxide (TiO_2) is one of the most preferred semiconductor metal oxides for the development of conductometric gas sensors due to its nontoxic nature, chemical stability, and commercial availability at a low cost, robust, and general reactivity. TiO_2 is electrically insulating with extremely high resistivity, but the sub-oxidized (TiO_2) with an excess of titanium is an n-type semiconductor with unique properties, indicating that the defect disorder and O/Ti stoichiometry play an important role in the electrical properties.

Rare earth and its properties

Rare earth metals include the lanthanide series from 58-71 atomic number, whereas others are La-57, Sc-27, Y-39, named as rare earth doped metals. They are further divided into two groups, which are lanthanides and actinides. Rare earth metals contain various other electronic properties that are further used in various applications. These metals are called rare earth due to the most abundant element in the earth’s crust, and they are extracted from certain oxide minerals. They are not found as free metal in the Earth’s crust. Rare earth minerals are not found in pure minerals; they are found as a mixture of rare earth metals. They make oxides when they react with oxygen gas. Rare earth has a very high melting point, and it forms ionic compounds. Some rare earths have +2 valency, while others have +4. +2 valency is found in those elements like samarium, europium, thulium, and ytterbium, while +4 valency is of cerium, terbium, and praseodymium. The electronic configuration is [Xe]4fn5d06s2, where n varies from 1 (Ce) to 14 (Yb). Rare earth elements are a group of fourteen that have similar physical and chemical properties. The electronic structure of these elements details the chemical and physical properties that are very similar. All of the rare earth elements have filled the lower orbital through 4d, whereas 4f and 5d orbitals are occupied. Lanthanum is considered the first rare earth element. Its electronic configuration is 4f05d16s2, and the 4f orbital contains 14 electrons, whereas 5d electrons are only contained by lanthanum, gadolinium, terbium, and lutetium. In the chemical compounds of these rare earth elements, the 5d and 6s electrons are involved in the orbital bonding. They are held by negative ions in the ionic compounds. As the atomic no. Increases, the increasing nuclear charge with a uniform outer electronic structure results in a slight decrease in the atomic radius. Whereas the shrinkage in atomic radius is attributed to their slight difference in their properties. These properties make them interesting ones that correlate with the various properties of metals and also with their atomic and molecular structure. Rare earth elements absorb and emit a narrow wavelength range. The intensity of the transitions is weak. They have a long lifetime of metastable states. Their quantum efficiencies, except in aqueous solution, tend to be high. They are mainly paramagnetic in nature, whereas at low temperatures, they are ferromagnetic or antiferromagnetic in nature. Rare earth ions Ce^{3+} to Yb^{3+} have partially filled 4f orbital, which have energy levels characteristic of each ion and show a variety of luminescence properties around the visible region. Their luminescence property is long-lasting and has a narrow bandwidth. The narrow band emissions are obtained from the visible region and the near IR region. Whereas, Yttrium is not a true rare earth element, which is in the group of heavier members of the rare earths. So, it is very difficult to separate from them. The chemical properties of yttrium will be similar to those of the rare earth metals.

Doping

Doping is used to control the properties of the semiconductor, and a new multifunctional material is obtained. There are various doping methods, including diffusion, ion implantation, and in situ doping with epitaxial growth. The pure semiconductors such as silicon (Si) or germanium

(Ge) are intrinsic semiconductors. Using extrinsic dopants, they readily contain n- or p-type dopants. For device fabrication, the doping and co-doping of the same silicon crystal from n- to p-type doping is very common. The wide band gap semiconductors, including ZnO, are asymmetrically doped. That is, they are not both type doped, but one can be n-type, and the other is p-type. This type of symmetry can be explained by the high activation energies of these dopants and the low solubility of the desirable dopants. Also, the a tendency to form defects spontaneously. Rare earth doped elements, such as Y-doped and Ce-doped materials, make efficient donors for producing an n-type ZnO material with low resistivity.

Nanocomposites

Individual materials have some limitations in performing a task, so more than one material together performs tasks easily and has some special properties of the materials. Together they perform a task which favourably shows various properties named as nanocomposites. The nanocomposites provide various properties such as mechanical, electrical, optical, thermal, and electrochemical. Nanocomposites can be classified according to material properties: ceramic-matrix, metal-matrix, and polymer-matrix. Among these metal-matrix nanocomposites show semiconductor nanocomposites. The binary nanocomposites and their properties, like photovoltaic, photocatalytic, and gas sensing, attract researchers like ZnO-CdO nanocomposite semiconductors. Optical and morphological properties of nanostructured Zn and Cd oxide mixture thin films have been reported previously [117.118]. The content ratio controls the optical properties and the band gap of nanocomposites. In recent years, nanocomposites have received a lot of attention because of their optoelectronic properties [119,120]. Among the reported work, CdO-ZnO, ZnO-TiO_2 composites offer properties such as various defects in the lattice like vacancies (V0), interstitial (Oi) oxygen atoms, and zinc atom vacancies (Vzn), interstitials (Zni), which increase the potential for optoelectronic applications [121].

Binary and Ternary oxides

Binary oxides like titanium dioxide, zinc oxide, and CeO_2, CdO, V_2O_5, MbO, etc., have been extensively used for the removal of organic pollutants like AZO dyes, methylene blue. Methylene red, congo dye, etc., various composites CuO-SnO_2, ZnO/γ-Mn_2O_3, ZnO/Mn_3O_4, ZnO/Fe_2O_3, ZrO_2-TiO_2, ZnO: MnO_2, TiO_2/WO_3, ZnO: TiO_2 [122-129] have been used for treatment of MB/MO, rhodamine B, etc. TiO_2 is the most common photocatalyst due to its availability, cost efficiency, and other good properties. Where the UV range 2000 nm-400 nm illuminates TiO_2, atoms are photoexcited and transferred towards the conduction band. So many e-h pairs are created, and an oxidation-reduction process may also be created. Whereas sunlight will also be used in the process of photocatalysis due to its low cost, sustainable, water disinfectant solar photocatalysis is mostly used, and also for water detoxification[130], whereas ZnO: TiO_2 and ZnO: CdO were used for the photocatalytic application under visible light irradiation.[131-133]. When the binary ZnO: TiO_2 and CdO: TiO_2 were synthesized, the result was obtained [134-137]. These multiphase $ZnTiO_3$ and $CdTiO_3$ are most suitable for photocatalytic treatment because they provide an efficient surface area for the catalyst reaction [138,139]. Also, coupling of the nanomaterials provides adequate modification in the optical bandgap, which makes them suitable for absorption of visible light [140]. Similarly, changes in the surface morphology were observed from nanoparticles to nanorods or nanoflakes, which directly interact with H_2O_2 under visible light. The photodegradation efficiencies under visible light are enhanced; besides this, unlike semiconductors, which provide dissimilar energy levels that support greater charge separation and reduced electron-hole pairs. Besides these semiconductors, similarly, changes in surface morphology were observed from nanoparticles to nanorods or nanoflakes, which directly interact with H_2O_2 under visible light. Consequently, the photodegradation efficiencies under visible light are enhanced. Ternary oxides such as rare earth doped and other metal oxide semiconductors like ZnO-MoS_2-TiO_2 [141-144], and Y, Ce, Al, Eu, Ag etc. doped ZnO: CdO, ZnO: TiO_2, ZnO: CdS, ZnO: SnO_2 were used for further various applications like gas sensing, photocatalytic, photovoltaic, solar cells, enhance the conductivity and other properties of binary oxides[145]. In addition, ternary metal oxides have different compositions, are such as ZnO/Fe_2O_3/MnO_2 [146], SnO_2/ZnO/TiO_2 [147], ZnO/Ag_2O/Fe_3O_4 [148], Fe_3O_4/ZnO/$CoWO_4$ [149], Fe_3O_4/ZnO/$NiWO_4$ [150], CdO: TiO_2 [151], ZnO: TiO_2:CdO [152] and CdO: TiO_2:ZnO [153]. Raliya et al. [154] used different compositions of TiO_2, ZnO, and GO for the degradation of methyl orange in visible light, and compositions were used as TiO_2, ZnO, TiO_2/ZnO, GO/ZnO, and GO/TiO_2 [155].

Mechanism of Gas Sensing Application

Gas sensors are used for both quantitative and qualitative purposes and are one of the devices that are used to identify the presence of various gases. There are many sensors, like optical, magnetic, biosensors, chemical sensors, and radiation sensors, etc. These sensors work for different purposes, and they are named for their parameters, such as optical and electrical sensors. Gas sensors are a basic need for society, and they provide safety for human life as well as for the environment. Due to rapid gas emissions by industries. Society is dealing with various polluted gases like Cl_2, NO_2, CO, etc. These gases are released from vehicles, industries, and human-useable things like LPG, CO_2, etc. These are used daily. In biology, these glasses are used when working on human organs like O_2 and CO_2. These gases are used for the body's functioning of the blood and lungs. These sensors worked not only for hazardous gases but also for O_2, N_2, and as harmless gases.

Type of sensors

Gas sensors can be divided into various types of sensors. Sensors are classified into the principle of operation of different gas sensors, including catalytic gas sensors, electrochemical, optical gas sensors, acoustic gas sensors, and semiconductor gas sensors.

Catalytic gas sensors

The first type of gas sensor was detected in 1923 by Jonson [156]. The catalytic gas sensors can be used for the detection of combustible gases. This type of catalytic sensor can be further divided into two parts: thermoelectric and polyester. It is used to detect methane in mines. Catalytic sensors have two beads containing platinum wire coils and are attached to opposite arms of the Wheatstone Bridge circuit, and have temperatures up to 100 °C. The target gas of resistance of active beads has changed with the voltage and recoils, and a large number of gases are required.

Electrochemical gas sensors

It consists of two electrodes, one is a sensing electrode, and another is a counter electrode of a sample of thin film [157]. Due to the electrochemical reaction of gases at electrodes, these types of sensors can show a flow of current between the sensing and the counter electrode. The amount of current is recorded to detect the concentration of gas. These sensors are basically used in refining, gas turbines, and chemical plants.

Optical gas sensors

One of the most commonly used sensors converts radiation into electrical signals. The sensors record the change in intensity of the photoluminescence and absorption spectra in the presence and absence of target gas [158].

Acoustic gas sensors

Acoustic wave gas sensors are mechanical sensors as the acoustic wave propagates on the surface of the material, which affects any change in the presence of gas, any wave changes, and these changes are recorded for sensing measurement [159]. While measuring the frequency or phase characteristics, there is a change monitored in the frequency. As the acoustic wave propagates through or on the surface of the material, which is affected in the presence of gas, any changes to the characteristics of the wave change and this change is recorded by sensing measurements [159]. Changes in velocity can be monitored by measuring the frequency or phase characteristics of the sensor and can be correlated to the corresponding physical quantity being measured. Acoustic wave sensors have a receptor, which is an element that is sensitive to an analyte, and a transducer. That is an element that converts the response into an electrical signal. Acoustic wave sensors have a receptor that is sensitive to an analyte and a transducer. The transducer is an element that converts a sensing response into an electrical signal.

Semiconductor gas sensors

These are made of metal oxide and used for measurements of gas concentration at a target gas by measuring electrical resistance [160]. The absorption of sample gas on the oxide surface is followed by catalytic oxidation. This results in a change in electrical resistance of the oxide materials, which shows n-type to reduce gas and p-type to oxidize the gases easily. They are very cheap and inexpensive. Some of the others are photoionization, infrared, ultrasonic, and holographic sensors.

Gas sensing mechanism

The metal oxide sensors improved the selectivity, sensitivity, fast response/recovery time, high reliability, and low power consumption, increasing the activity of the metal oxide semiconductors. On improving the sensing performance by changing the shape and size of the materials. The fewer particles may lead to enhanced properties of metal oxide sensors and also increase sensor response/recovery time. So, for nanostructured particles, metal oxide semiconductor sensors increase their efficiency. The smaller sizes of nanostructured metal oxide semiconductors may lead to increased structural and morphological properties. So, metal oxide semiconductors are better used to improve the nanostructures of pure and mixed metal oxides. The resistive gas sensor is used for its larger area. A solid-state gas sensor device is generally composed of a layer of sensing elements deposited on patterned ceramic substrates. The sensor response may be presented as S=R0/R, where 'R0' is the resistance in air and 'R' is the resistance in the presence of the target gas. This sensor response is also characterized by the response time and recovery time. The thickness of the thin film may depend on response time and recovery time, both slow at low temperatures and fast at high temperatures. A metal oxide semiconductor is mostly used as the sensing element of gas sensor applications. As the electrical conductivity changes, it changes the different gas compositions. Metal oxide semiconductors have shown a change in resistivity towards different gas targets.

Mechanism of photocatalytic application

For a sustainable future, nanotechnology has attracted great attention in the last few years. For particular applications, nanochemistry makes use of synthetic and material chemicals to obtain nanomaterials with variable shape, size, and to design a specific function. Nanotechnology has been used to obtain valuable information for the synthesis of materials due to their specific properties and reproducibility. So a particle, the term photocatalysis, may be made up of two words, like photo and catalyst, that is. That is related to the photon. Here, a catalyst means the material in which the current substrate shows the reaction rate. So these chemical reactions take place in the presence of a material known as a photocatalyst. Photocatalysis is the reaction that takes place between light and a semiconductor. So, the photocatalyst is a substrate that acts as a catalyst and absorbs light. Various sources say all the photocatalysis is used as semiconductors. The exposure of electrons and pairs is generally known as photocatalysis.

Based on the physical state of reactants, photocatalysts are of two types-

Homogeneous photocatalyst- A Homogeneous photocatalyst is known as a solid, liquid, or gas semiconductor that is of the same phase.

Heterogeneous photocatalyst- Heterogeneous photocatalysts are known when semiconductors and reactors are in different phases. It is also known as a solid catalyst.

Conclusion

Nano-metal oxides have emerged as an important class of nanomaterials due to their unique size-dependent characteristics and enhanced physical, chemical, and structural properties. Compared to their bulk counterparts, these materials exhibit higher surface area, improved reactivity, tunable optical and electronic properties, and superior catalytic performance. This review highlights that the characteristics of nano-metal oxides are strongly influenced by factors such as particle size, morphology, crystal structure, surface defects, and doping elements. The reviewed studies demonstrate their wide applicability in diverse fields, including gas sensing, photocatalysis, environmental remediation, energy storage, biomedical applications, and optoelectronic devices. Despite significant progress, challenges such as large-scale synthesis, control over particle agglomeration, long-term stability, and environmental safety still need to be addressed. In conclusion, nano-metal oxides hold great promise for future technological advancements. Continued research focused on improving synthesis techniques, enhancing stability, and understanding structure–property relationships will further expand their potential in next-generation applications.

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