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Recent advances in ZnO nanostructures and their future perspective

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Abstract. This review addresses the recent developments of the processing of ZnO nanostructures (NSs) and characterizations of the developed NSs by various techniques, mainly hydrothermal technique. This article discussed various kinds of ZnO NSs such as wires, rods, flowers, dumbbells, spheres, particles and combs created by hydrothermal process on carbon fibre substrate. ZnO likely has the wealthiest group of NSs among all materials, both in structures and properties. The NSs could have novel applications in sensors, transducers, optoelectronics, and biomedical sciences. This article moreover studies the distinctive NSs of ZnO created by the different procedures and upgrades in the mechanical, electrical and thermal properties of the subsequent progressive composites. ZnO NSs processed on any substrate makes a hierarchical structure and can altogether enhance the specific properties in the final nanocomposites. Article also discussed the potential of ZnO NSs for fiber reinforced nanocomposites, focusing on the most used techniques used for the creation of ZnO NSs reinforced hierarchical composites and surveys the potential for another age of cutting edge multifunctional materials. Recent concepts used for improving or synthesizing other distinctive NSs having tailored properties are also explained in the article.

Keywords: hydrothermal process; nanocomposites; nanostructures; zinc-oxide

1. Introduction

In the present scenario of materials, ZnO is a prime and innovative material. Their nonappearance of the state of merging of symmetry in wurtzite, joined with huge electro-mechanical coupling, accomplishes favorable piezoelectric and pyro-electric qualities and the accompanying utilization of ZnO in piezoelectric sensors and mechanical actuators (Pirhashemi *et al*. 2018). Additionally, ZnO is a wide band gap (3.37 eV) compound semiconductor that is appropriate for short wavelength optoelectronic usage. The high exciton confining criticalness in ZnO crystal can guarantee gainful excitonic transmission at room temperature and ultraviolet shimmer has been represented in scattered nanoparticles and thin films (Baruah and Dutta 2009, Król *et al*. 2017, Xu and Wang 2011). ZnO is direct to visible range of light and can be prepare ultra-conductive by doping (Król *et al*. 2017, Sánchez Zeferino *et al*. 2011). ZnO is a versatile utilitarian material that has a varying function of change morphologies like nanorings, nanobelts, nanocombs, nanocages and nanowires (Hsu and Chang 2014, Kozuka *et al*. 2014, Kumar and Rao 2015). Since 2000 and particularly lately, the ZnO based nanocomposites has increased more consideration in light of the fact that ZnO is a remarkable matter which displays piezoelectric and semiconducting dual properties (Sun *et al*. 2010). Specialists discovered inspiration to build up a material which has elite and the novel applications in the field of innovative upgrade, for example, optoelectronics, sensors, transducers and biomedical sciences (Boro *et al*. 2018, Djurišić *et al*. 2012, Gu *et al*. 2016, Rai 2013). ZnO based groups of NSs such as nanowires are frequently utilized for an extensive variety of utilities from power devices to solar products to semiconductor devices (Chen *et al*. 2013). Morphologies of the nanowires with the surface of carbon fibers are the prime factor to enhance the structural properties of the nanocomposites (Rai and Bajpai 2019). All together for the interphase of nanowire to develop interactions between the interfaces of composites, which must offer upgraded bonding between the polymer lattice and base fiber. While bonding with the base fiber, the extended surface domain and mechanical interlocking of the nanowire covering ensured and upgraded collaboration with the polymer grid. This reaction was guessed to be an eventual outcome of the collaboration of ZnO with oxide groups like carboxylic acid. But the correct interactions have not been estimated, it is striking that ZnO collaborates unequivocally with COOH groupings. There have been a couple of examinations of how ZnO associates with the COOH groupings regardless, compact conclusions on the correct strength of such an association presently cannot appear to be resolved (Wang 2004). Distinctive systems for synthesizing ZnO nanowires have been outlined, including the aqueous method, template based development, thermal dissipation, plasma beam epitaxy, CVD, and MOCVD (Fujisawa *et al.* 2013, Hasnidawani *et al.* 2016, Naveed Ul Haq *et al.* 2017, Shirvanimoghaddam *et al.* 2017). The aqueous procedure is frequently used to produce ZnO NSs with generally negligible cost at very low temperatures. In this system, NSs are gained by varying the precursor chemicals, fixation, reaction time and development temperature (Rai

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and Bajpai 2020). Regardless of the way that it was extremely difficult to manage the development of ZnO NSs, a restraint way of development of NSs of zinc oxides has accomplished by Liang *et al*. (2012).

Here in this study, the advancement of ZnO NSs regarding synthesis, morphologies, characterization and potential applications are altogether examined. This article also contemplates the particular NSs of ZnO made by the various systems essentially aqueous technique and the role of ZnO in controlling properties like mechanical, electrical, thermal, sensing, dielectric, piezoelectricity, conductivity, energy storage and antimicrobial features of resulting materials. The essential standards of the amalgamation and principle parameters which impact the shape and strcuture of the items are examined with the assistance of structural and morphological characterizations. At that point, various applications dependent on the ZnO progressive NSs are explained with regards to possible applications. The role of ZnO NSs in advance materials and techniques to improve the capability of ZnO nanomaterial are additionally examined. Ongoing ideas utilized for improving or integrating other particular NSs having tailored properties are likewise clarified in the article. Concise illustrations of significance of these studies for diverse utilities of ZnO NSs are carried out. It has been uncovered that, the inclusion of an improved measure of ZnO or its subsidiaries to various media arises as a great strategy to accomplish elite nanomaterials for differed applications. This article likewise sums up the prospects of ZnO NSs for elite polymer composite materials for underlying applications. The investigations of ZnO NSs in polymer nanocomposites are likewise depicted which demonstrate the current difficulties in ZnO/polymer nanocomposites. The Current circumstances of the ZnO NSs and challenges looked by the analysts to accomplish promising outcomes in the field of advance material applications are illustrated. At last, the future perspective of the development and utilizations of ZnO NSs are also discussed.

2. Synthesis techniques of ZnO NSs

The amalgamation techniques of various ZnO NSs can comprehensively be classified in the following manner:

a) Solution phase synthesis:

In this method the development procedure is performed under liquid phase. The procedure is known as hydrothermal process because of utilization of typical aqueous solution. Following portions are involved in the solution phase synthesis processes:

1. ZAH in alcoholic solutions with NaOH or Tetra Methyl Ammonium Hydroxide
2. Spray pyrolysis for growth of thin films
3. Electrophoresis
4. ZAH derived nano-colloidal sol-gel route
5. Template assisted growth

b) Gas phase synthesis:

This process utilized gaseous atmosphere in enclosed containers. Generally this process is happened at high temperatures in the range of (500-1500) °C. Following are the usually available methods of gas phase are:

1. CVD (Chemical vapour deposition)
2. Metal oxide CVD
3. Thermal oxidation of pure Zn and condensation
4. Vapour phase transport, which consist of vapour solid (VS) and vapour liquid solid (VLS) growth
5. Physical vapour deposition
6. Microwave assisted thermal decomposition

2.1 Hydrothermal synthesis (ZAH based) of ZnO NSs

“Zinc acetate based nanocolloidal sol-gel course”, when this approach was proposed, the claimed "size quantized Q-ZnO" nano-colloids were successfully clarified and their key optical features especially revealed. The genuine disadvantages of such solutions having low concentration as ~1 mM were their obliged robustness and utility potential, fundamentally kept to vital spectroscopic examinations (Hasnidawani *et al*. 2016). This issue could be overpowered by displaying the sol-gel idea that allowed raising the volume segment of non-accelerated ZnO colloids by small rate of variation, down to between molecule partitions pushing toward one atom separate over. This new approach yielding straightforward completions opened us new possible results of making thin films and nanocomposites (Zhao *et al*. 2014). It also enabled a controlled association, shape adjustment and outlining on the nano and micro scale. Sol-gel technique was picked up a ton of prominence as it allows restrained combination, shape regulation and designing of the NSs (Hou *et al*. 2013). A transparent solution will form when concentrated ethanolic ZAH suspension was refluxed and distilled. Under high fixation conditions small ZnO nanoparticles of measurement of 5nm (approx.) can be developed by the aid of hydroxides such as LiOH, NaOH. For the development of ZnO NSs there are several literatures of changes of the ZAH dehydration or disintegration and further condensation (Jung *et al*. 2012, Foo *et al*. 2014). The scan for essential bunches to fill in as building hinders for different NSs has been continuing for a long while. The detachment and recognizable proof of essential bunches is a region of dynamic research. The blend of essential structures relies upon different situations like the amalgamation temperature, initial concentration of the salt, nature of the solvent and warming time. The ZnO groups can be individuals from any of the three unique families mentioned beneath:

(1) The $Zn_4O(Ac)_6$ named as “basic zinc acetate” and their greater itself similar homologue $Zn_{10}O_4(Ac)_{12}$,

(2) The ethoxy-acetate $(EtOZnAc)_n$ for creating wire-shape Nano-features and

(3) The hydroxy-acetate $Zn_5(OH)_8(Ac)_2(H_2O)_2$ monomer of lamellar sheet compounds, also named as “hydroxy double salt” (Zn-HDS).

The $Zn_4O(Ac)_6$ amass is encircled in ethanol and 1-propanol at temperatures more than 50°C as observed by researchers in XRD and Raman spectroscopy estimations (Hilgendorff 1998). All the more as of late, Tokumoto *et al*. (2003) successfully proposed a depth study time settled EX-AFS examine joined with UV-VIS optical analysis and FTIR-spectroscopic outcomes. Researchers unreservedly and unambiguously exhibited the appearance and expanding groupings of these tetrahedral bunches by deferred refluxing of ethanolic ZAH arrangements (Absalan and Ghodsi 2012, Znaidi 2010). The entire test perceptions exhibit that underlying heating advance can be depicted by the going with complete reactions

$$4\mathrm{Zn(Ac)_2 \cdot 2H_2O} \xrightarrow{\mathrm{Heat}} \mathrm{Zn_4O(Ac)_6} + \mathrm{7H_2O} + \mathrm{2HAc} \quad (1)$$

$$4Zn_4O(Ac)_6 \xrightarrow{yields} \mathrm{Zn_{10}O_4(Ac)_{12}} + 6\text{“}\mathrm{Zn(Ac)_2}\text{”} \quad (2)$$

$$Zn_4O(Ac)_6 + Zn_{10}O_4(Ac)_{12} \xrightarrow{yields} Zn_{13}O_5(Ac)_{16} + \text{“}Zn(Ac)_2 \quad (3)$$

$$Zn_4O(Ac)_6 + Zn(Ac)_2 + 9H_2O \xrightarrow{yields} Zn_5(OH)_8(Ac)_2(H_2O)_2 + 6HAc \quad (4)$$

$$Zn_{10}O_4(Ac)_{12} + 16H_2O \xrightarrow{yields} 2Zn_5(OH)_8(Ac)_2(H_2O)_2 + 8HAc \quad (5)$$

$$Zn_{10}O_4(Ac)_{12} + 8H_2O + 8OH^- \xrightarrow{yields} 2Zn_5(OH)_8(Ac)_2(H_2O)_2 + 8Ac^- \quad (6)$$

2.1.1 Stability of ZAH derived NSs

To dissect the stability of the ZAH-inferred clusters, inadequate charge estimations utilizing the model of Henry-Livage (Henry *et al.* 1992) have been completed. The foreseen design is found in Table 1 mirroring a consistency with the above stated test considers (Henry *et al.* 1992, Luković Golić *et al.* 2011). The antecedent packs are recorded by the expanding thermodynamic quality. This might be watched that bunches of tetrahedral oxy-acetate have fairly more stability than the highest responsive ZAH. Additionally, the dependability of the auxiliary $Zn_{10}O_4(Ac)_{12}$ antecedent is positively extended inside seeing 1-H_2O and 7-EtOH, continually found in synthetic examination. The more noteworthy solidness of monomer (Zn-HDS) concerning the exposed oxy-acetic acid derivation clusters anticipates that once a specific measure of water is accessible, an unconstrained and specific course of action of Zn-HDS can be normal that also agrees with produced literatures. Authors have figured charge course in the advance state contrasting with the response between oxy-acetic acid derivation and water and saw an unconstrained improvement of Zn-OH under HAc release. The zinc ethoxy acetate is most stable precursor bunch and without a doubt, this is experimentally affirmed. In spite of the fact that, in a moderate response constrained process, these groups develop to huge single crystal in ethoxy-acetic acid derivation sols (Hong *et al.* 2017).

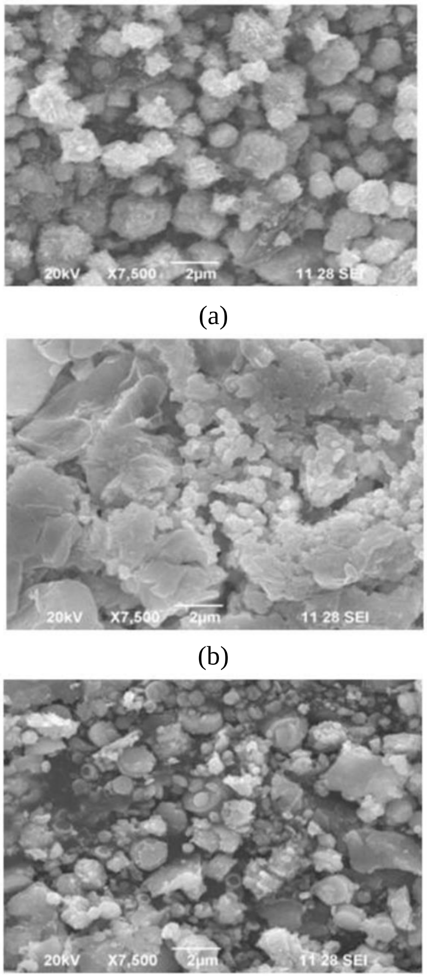
3. Morphologies of ZnO NSs

3.1 Nanoparticles

Despite the fact that the organo-metallic blend of nanoparticles of ZnO in atmosphere of alcohol has gotten more extensive acknowledgment for reasons of speedier nucleation and development when contrasted with water. In this survey the distinguished reports of aqueous amalgamation in fluid medium are accessible. Baruwati *et al.* (2006) were revealed the liquid amalgamation of nanoparticles of zinc oxide utilizing $Zn(NO_3)_2.6H_2O$. Blend was done in autoclave at 120°C in the wake of changing the pH to 7.5 utilizing NH_4OH. In the wake of cleaning, the particles were kept at 80°C medium-term for procuring into the powdered form by drying. Bhattacharyya *et al.* (2017) first uncovered that nanoparticles of ZnO can be used for potential antimicrobial specialist, they surveyed the antimicrobial and hostile to biofilm development of ZnO nanoparticles in contrary to bacterium Streptococcus pneumoniae which is a basic explanation behind sickness. ZnO nanoparticles demonstrated solid antimicrobial action in contrast to S. pneumoniae, with a MIC estimation of 40 lg/ml. The literature shows that sub-MIC dosages of ZnO nanoparticles show capable antagonistic to biofilm activity contrary to S. pneumoniae. Along these lines, ZnO nanoparticles may fill in as a major aspect of a blend treatment contrary to medicate resistant S. pneumoniae contaminations, where biofilm arrangements accept an essential part in disease progression. Das *et al.* (2015) arranged organic-inorganic heterogeneous hybrid anion leading films utilizing 1,4-diglycidyl butane ether with the aid of synthetic nanoparticles of SiO_2 onto polyvinyl alcohol (PVA). They showed that PVA cross-connected with at room temperature added to the DGBE and SiO_2 upgrade of rigidity and conductivity in comparison to their uncross-connected portion. Deka *et al.* (2012) effectively created Wood polymer nanocomposite by utilizing HDPE, LDPE, PP, PVC, wood powder, polyethylene-co-glycidyl methacrylate, and diverse nano-sized particles of ZnO, clay, and SiO_2. By the joining of such nanoparticles the UV protection properties get progressed. Bacterial deployment of composite was also enhanced by the aid of clay and nanoparticles. Brintha and Ajitha (2015) effectively synthesized nanoparticles of ZnO by various strategies such as hydrothermal techniques, sol-gel method and aqueous emulsion and the arranged nanoparticles were analyzed by SEM, EDX, XRD and UV. Fig. 1(a) outlines the SEM results of zinc oxide nanoparticles produced by aqueous solution technique. The image indicates spherical and

Table 1 ZAH derived precursors groups with their Partial charge distribution (δ_i) in based on H-L model based estimations using Allred-Rochow electronegativity (χ_O = 3.5, χ_C = 2.5, χ_H = 2.1, χ_{Zn} = 1.66); where, EtO = OC_2H_5 ligands, χ_m = mean electronegativity

Precursor clusters	δ_{Zn}	δ_{Ac}	δ_{H20}	δ_{OEt}	δ_{OH}	χ_m
$Zn(CH_3COO)_2 \cdot 2H_2O$	0.471	-0.227	-0.011			2.485
$Zn(CH_3COO)_2$	0.469	-0.235				2.482
$Zn_4O(CH_3COO)_6$	0.467	-0.245				2.479
$Zn_{10}O_4(CH_3COO)_{12}$	0.465	-0.254				2.476
$Zn_5(OH)_8(CH_3COO)_2 \cdot 2H_2O$	0.463	-0.269	-0.027		-0.22	2.471
$Zn_{10}O_4(CH_3COO)_{12} \cdot H_2O \cdot 7EtOH$	0.429	-0.462	-0.111			2.412
$EtOZn.CH_3COO$	0.411	-0.567		0.16		2.379



(a)

(b)

(c)

Fig. 1 (a) SEM image of ZnO nanoparticles (Aqueous solution method), (b) SEM image of ZnO nanoparticles (sol-gel method), (c) SEM image of zinc oxide nanoparticles (hydrothermal method) (Brintha and Ajitha 2015)

flower like structure. Fig. 1(b) demonstrates SEM pictures of the ZnO nanopowders arranged by sol-gel technique. The ZnO nanoparticles have blossom like shape. Similar outcomes observed in structural and optical portrayal of nanopowders of Ni and Ni-Al co-doped with ZnO orchestrated by means of the sol-gel process (Sayari and El Mir 2015). Fig. 1(c) demonstrates the SEM image of ZnO nanoparticles arranged by hydrothermal strategy. The zinc oxide particles arranged are round shape. It likewise demonstrates that a network formation of the zinc oxide nanoparticle has occurred which clearly shows that agglomeration has occurred. Ramimoghadam *et al*. (Ramimoghadam *et al*. 2013) produces NSs of ZnO by means of hydrothermal technique utilizing uncooked rice (UR) form as a bio-resource that can be used as bio-template for directing the morphology of nanoparticles. The influences of the rice on ZnO properties were investigated. Mechanics of the development of the ZnO crystal is conceivable coordinated by conjugated and contending amalgamation of Zn and starches.

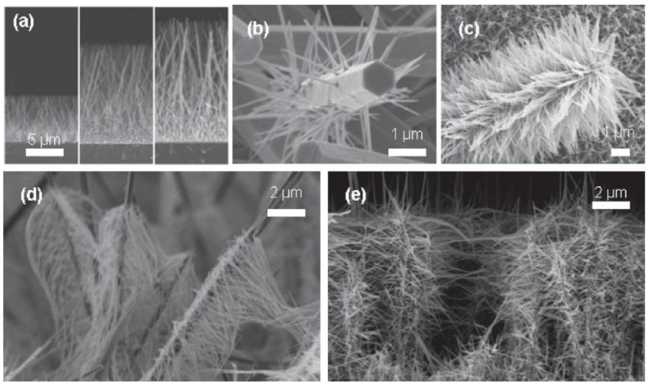


Fig. 2 SEM image of ZnO NWs (a) Growth of length (b) with no seeds (c) with seeds after polymer removal (d) without polymer removal and (e) with polymer removal after seed NP deposition (Ko *et al*. 2011)

3.2 Nanorods and nanowires

Nanorods and nanowires of metal oxides have been developed various researchers to achieve tailored properties for high performance material applications. Some of the prominent work is discussed in this section. Most of the researchers use hydrothermal technique for enhanced morphologies of ZnO NSs such as Deka *et al*. (Deka *et al*., 2015) adequately made CuO nanowires encapsulated in WCF polyester resin composites utilizing VARTM procedure. Initially seeding of CuO on WCF is done then nanowires on that portion were allowed to grow via hydrothermal synthesis. The development of nanowires completely depends upon the seeding cycles and there are no influences of concentration of development solution and development time on the growth of nanowires. Due to the development of nanowires on WCF, properties like strength and tensile modulus will increase by 42.8% and 33.1% respectively. Ko *et al*. (2011) demonstrated nanoforest by means of a simple selective hierarchical development that would fundamentally enhance the efficiency of DSSC power converter. Developed nanoforest consist of high density long branched tree-like various leveled crystalline ZnO photoanodes. The effectiveness of overall light transformation and short circuit current density of the stretched nanowires DSSCs were appropriate around 5 times greater than the productivity of upstanding ZnO nanowires. The productivity augmentation is because of significantly enlarged surface territory enabling greater dye stacking and light collecting, and in addition diminished charge recombination through direct conduction along ZnO nanotree branches. The foundation of leveled ZnO nanoforest is basically a cluster of vertically adjusted long ZnO nanowires (Fig. 2). Figs. 2(b) and 2(c) portray the “seed effect” and Figs. 2(d) and 2(e) exhibit the “polymer removal effect”.

Hazarika *et al*. (2015) effectively created ZnO nanorods on woven Kevlar fiber (WKF) via hydrothermal strategy as a way to deal with upgrade the interfacial stronghold of aramid composites. Initially the WKF was treated by surface hydrolysis and an ion-exchange procedure to consolidate –COOH group on the filaments of WKF to upgrade the attachment of ZnO to main strands. Dependency of development of ZnO nanorods were examined by SEM results and it was found that the development of nanorods completely relied upon quantity of seeding, time for treatment and the convergence of ZnO utilized. The impact of time, pH, focus, and temperature on the morphology of ZnO NSs was considered by Amin *et al.* who detailed consistent and enduring development of ZnO nanorods up to 10 h of synthesis (Amin *et al*. 2011). Kong *et al*. (2013) created ZnO NRs on WCF utilizing hydrothermal strategy. The VARTM technique was utilized to totally mix the ZnO/WCFs with polyester resin. The test results demonstrate that the developed ZnO will enhance the energy absorption because cross connected network transfers energy through interfaces and also enhances the load exchange and interfacial strength. Ruqeishi *et al.* (2019) successfully developed a piezoelectric nano-generator by producing ZnO nanorods on inner side of horizontal quartz tube. Nanorods were successfully made and used as an alternating electric current producer. Tube-in-tube CVD technique was used to grow 3-5 g of ZnO NRs in every cycle which is sufficient to respond mechanical stress by producing current. Salahuddin *et al*. (2015) effectively created ZnO nanotube with mean external diameter and span of 200 nm and 2.4 µm separately by hydrothermal strategy. The FTIR demonstrated the characteristic absorption groups at 508 and 404 cm-1. These two retention peaks connect with the mass To-phonon frequency and the Lo-phonon frequency. The XRD investigation affirmed that the ZnO nanotubes have the hexagonal wurtzite structure. The optical properties were estimated by UV spectroscopy. Ghasaban *et al*. 2017) experimentally accomplished needle-like and plate-like morphologies of ZnO in a higher scale (60 g) of creation by means of a hydrothermal response performing in low temperature of 115°C and low response time of 2 or 6 h. They suggested that the hydrothermal response can be a reasonable technique to orchestrate ZnO NSs with the particular size and morphology and it is able to do simple scaling up. When ammonia (pH = 9) is utilized as an anionic antecedent, a needle-like morphology with a mean diameter 240 nm is shaped. As the anionic antecedent was supplanted by sodium hydroxide (pH = 13), the morphology is changed to plate-like NSs with mean diameter under 50 nm. XRD investigations of ZnO nanoparticles are appeared in Fig. 3. Both ZnO NSs have comparative XRD designs, aside from relative pinnacle intensities, because of their irregular orientation. XRD designs were recorded by hexagonal wurtzite shape of ZnO (a = 3.249Å, c = 5.206Å; JCPDS card no. 36-1451). XRD designs speak to sharp and solid signals supporting that the item is an exceedingly crystalline material. Utilizing Scherrer condition, the crystallite size (L) of the particles can be resolved as takes after (Khorsand Zak *et al*. 2011):

$$L = \frac{K\lambda}{\beta s} COS\theta \rightarrow cos\theta = (K\lambda/L)(1/\beta s)$$

where, L is crystallite size in nm, λ is the radiation wavelength (1.540 56 Å for CuKα) in nm, βs is the full width (at half-maximum) of ZnO diffraction crest profile in radian, *θ* is the diffraction angle (top position) and K is the shape factor (0.89 < K < 1) which is viewed as 0.94 here.

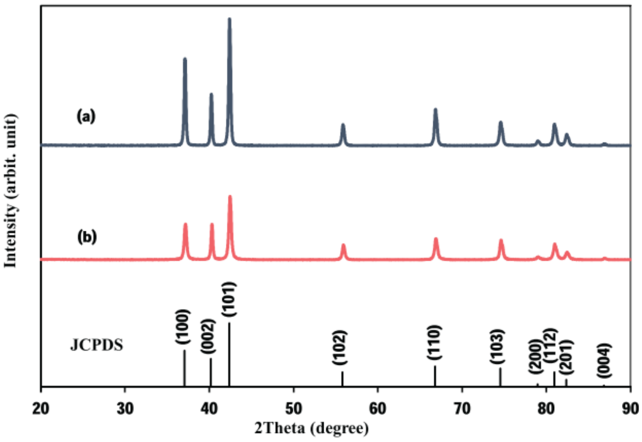


Fig. 3 XRD results of (a) needle-like (b) plate-like ZnO NSs (Ghasaban *et al*. 2017)

It is important to decide the instrumental expanding and correct the deliberate β as following:

$$(\beta s)^2 = (\beta measured)^2 - (\beta instrumental)^2$$

As indicated by Scherrer condition, the crystallite size can be acquired by plotting Cos*θ* versus 1/βs and figuring L parameter from the slant of regression line going through the origin facilitates. The other technique is directed by making logarithm on both sides of equation (1) as following (Monshi *et al*. 2012):

$$\beta_s = \left(\frac{K\lambda}{L}\right)\left(\frac{1}{cos\theta}\right) \rightarrow ln\beta s = \ln\left(\frac{K\lambda}{L}\right) + \ln\left(\frac{1}{cos\theta}\right)$$

By drawing ln(β_s) versus ln(1/Cos*θ*), a straight line with a slant of around one and an intercept ca. ln(K/L) must be found. Yilmaz *et al*. (Yilmaz *et al*. 2016) viably applied hydrothermal technique and chemical spray pyrolysis to successfully create nanocubes and nanorods. Amount of Zn^{2+} ion assumes a critical part for different shapes of the nanoparticles. Presence of nanoparticles of ZnO indicates great photo-iridescence so that synthesized product can have optoelectronic utilities. Grain size (D) and dislocation density (δ) have been estimated with the help of mathematical relations given by Scherer (Yilmaz 2015) as mentioned below.

$$D = \frac{0.9\lambda}{\beta cos\phi}$$

$$\delta = \frac{1}{D^2}$$

From above relations, λ represents incident X-beam's wavelength, β represents FWHM and Φ represents Bragg's angle.

3.3 Blossoms and cabbage-like NSs

NSs like as blossoms are extremely rare of zinc oxide and can be created utilizing hydrothermal techniques. The development of blossoms like ZnO utilizing hydrothermal technique has revealed by Yoo *et al*. (2017) demonstrated

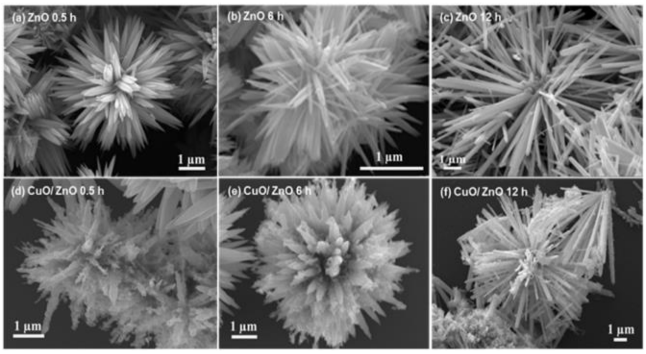


Fig. 4 SEM images of the surface morphology of both (a)-(c) ZnO and (d)-(f) ZnO/CuO structures as a function of ZnO synthesis time (Yoo *et al*. 2017)

amalgamation of nanopowders of CuO on high surface region of ZnO blossoms via hydrothermal technique. Resulting materials have exceptionally sensitive dimethyl methyl phosphate (DMMP) gas detecting qualities. Affirmation of the arrangement of CuO/ZnO heterojunction was assessed by PXRD and TEM examinations. Fig. 4 indicates the results of SEM examination of both ZnO and CuO/ZnO morphologies in the function of time. Blossom molded ZnO structures were framed and by expanding ZnO production time, the span of the bloom expanded from around ~3-3-10 µm in diameter. In the wake of blending of CuO in ZnO blooms, CuO nanoparticles were consistently kept of the top of the blossoms as depicted in the Fig. 4(d)-4(f). Xu and Wang (2018) successfully grown hierarchical ZnO crystals on polyimide (PI) film without any additional seeds under hydrothermal condition. The morphologies of ZnO crystals can be tuned just by changing the concentration of zinc ion solution. Stearic acid (SA) can self-assemble into nanoflowers when ZnO modified PI film was immersed into SA solution. The surface wettability of the films were tuned by the self-assembly of SA. On the contrary, concentration of Zn exhibits a significant role in determining the morphologies of ZnO on PI film. For better understanding the surface wettability transition of PI(ZnO-SA) films, they further investigated their surface morphologies. Compared with PI(ZnO) films, newly belt or sheet-like morphologies were found. Original morphologies of ZnO flowers on PI film show slightly change after stearic acid (SA) solution immersing procedure, which is attributed to the wet chemical fabrication process in the presence of SA (Kwak *et al*. 2009). Guo *et al*. (2010) proposed a novel method for the selective growth of 3D ZnO flower-like NSs. The flower-like structure could be varied by adjusting hydrothermal reaction conditions and laser irradiated parameters. This approach offers synthetic flexibility in controlling film architecture, coating texture and crystallite size. The control of flower density is another important aspect in spatial organization. It is also worth to mention that no NSs are observed in the un-irradiated area. Abdelfatah and El-Shaer (2018) detailed the creation of ZnO clusters using hydrothermal technique which developed vertically on FTO substrates. Molarity of KOH guided the strategy of development procedure. The outcomes demonstrated that ZnO exhibits along [0 0 2] plane. These ZnO rod clusters next to lowest diameter will create the favorable optoelectronic systems. ZnO nanorods and nanoflowers gives high extent of volume to surface with respectably high sensitivity both are required to great extent of practical and redesign sensor execution in characteristic appliances (Sabry and AbdulAzeez 2013). Fan *et al*. (Fan *et al*., 2014) viably made enormous measure of nanoflowers of ZnO on graphene/SiO_2/Si substrate by aqueous technique. Findings of the XRD examination conforms the presence of pure wurtzite stage in nanoflowers. Star-like morpghology were seen in the prepapred nanoflowers of ZnO. ZnO nanoflowers were displayed in narrow band gap in comparison to powders of ZnO because of the presence of O-vacancy.

Venkatesha *et al*. (2012) utilizes electrochemical strategy to orchestrated bloom molded zinc oxide microstructures. Controlled development of these structures was conceivable at bring down current densities and electrolyte focuses. Notwithstanding, sporadic development occurred at higher current density with a little abatement in the band gap of this semiconductor. Sun *et al*. (2012) mentioned an easy aqueous strategy to specifically create bloom-like microstrcutrues of ZnO via high photocatalytic movement. By changing the molar extents of Zn^{2+} to caustic soda, morphologies of the acquired samples can be control. At a point, when the free $[Zn(OH)_4]^{2-}$ contents were satisfactory, the hexagonal biprism-like and bar-like shapes were developed. Be that as it may, the conditions of ZnO center would change into oblate-like, nut-like, hexagonal circle-like and blossom-like when the free $[Zn(OH)_4]^{2-}$ contents were for the most part phenomenal. Additionally, bloom-like examples display great photocatalytic movement for decoloration of methylene blue (MB). Pant *et al*. (2013) successfully utilizes the facile one-pot hydrothermal process for blending blossom shaped ZnO particles progressively collected with Ti and Ag nanoparticles. The developed composite demonstrated brilliant photocatalytic execution which is credited to a moderate electron acceptor supporting the trading of photogenerated electrons from the conduction band. The size of the produced structures diminished by adding TiO_2 and $AgNO_3$ blend in hydrothermal framework. The conceivable reason for diminish in bloom size may be because of the reduction in per unit volume of ZnO concentration in aqueous course of action. Liu *et al*. (2015) prepared diverse blossom-like ZnO hierarchical designs by $C_4H_6O_6$ (Tartaric acid) aided hydrothermal technique particularly four bloom shape NSs were gotten all the while under a similar response condition. When spherical shaped nanoparticles get amassed then the resulting structure looks like a cauliflower shaped ZnO. Similarly by gathering of hexagonal rods and prism, other blossoms-like structure can be developed. TA goes about as a topping operator and structure-coordinating agent in the midst of combination. Affirmation of the oxygen opening for the most part originates from the ZnO surface as explained in XRD, PL and Raman spectra. The blossoms-shaped specimens of 1:4.5 and 1:3 with the higher aspect proportions have most astounding photocatalytic execution. The upgraded photocatalytic execution is predominantly incited by oxygen opportunity of ZnO.

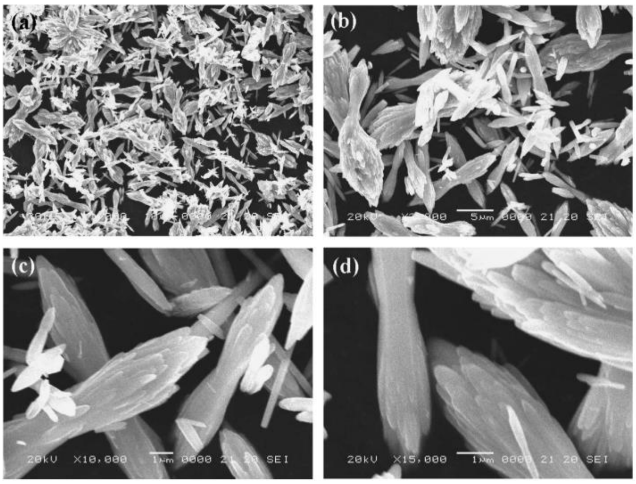


Fig. 5 SEM analysis of dumbbell-shaped ZnO at various magnifications: (a) and (b) low magnification; (c) and (d) high magnification (Wang *et al*. 2013)

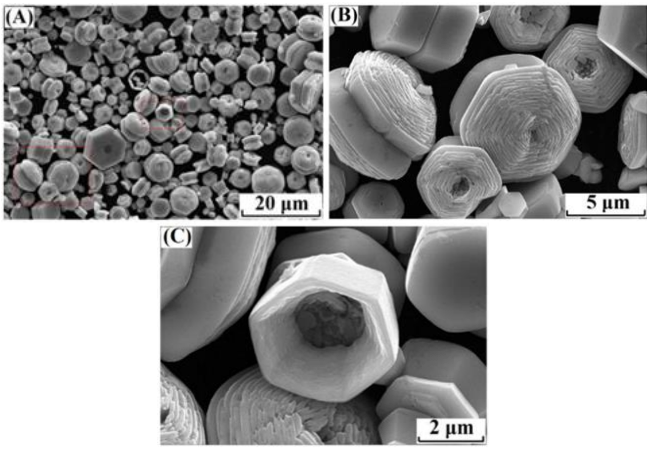


Fig. 6 (a) SEM image of ZnO NSs; (b) twinned flower-like ZnO; (c) hexagonal nut structure (Sun *et al*. 2016)

3.4 Other shapes

Several other shapes of the NSs have been developed by prominent researchers such as nanodumbell, nanoflakes, nanodisk, twinned dumbbelss and double disk. Guo *et al*. (2015) effectively produced the twinned ZnO disks using CTAB assisted aqueous technique at lower temperature. Literatures recommended that, by the expansion of duration of development the size and intensity of UV NBE peak diminishes. For the imperfection associated visible outflows, it increment with the time taken for development. In light of the preliminary outcomes, CTAB and improvement temperature are proposed as main segments for the formation of twinned plates molded ZnO. Wang *et al*. (2013) have been incorporated dumbbell-formed ZnO microstructures by utilizing an effortless aqueous technique. The obtained shape of ZnO is around 5-20 µm in length and diameter of two closures and center part are around 1-5µm and 0.5-3 µm separately. Fig. 5 represents different magnified pictures of SEM examination of produced dumbbell-like ZnO. Sun *et al*. (2016) effectively developed twinned blossom like ZnO structure by CTAB helped low temperature aqueous technique. The principle emanation peaks is identified with the bound exciton recombination of the acceptor as demonstrated by the temperature dependent PL spectra, it also demonstrates a decent crystal nature of specimens. In perspective of the preliminary outcomes, the self-etching and regrowth are proposed as the reason behind the improvement of stream-like structures. The aftereffects of as-developed twinned bloom like ZnO structures are outlined in Fig. 6(a). The magnified twinned bloom-like ZnO structures is portrayed in Fig. 6(b). The outside forms of the twinned bloom-like ZnO particles are as yet exhibited the hexagonal profile, as differentiated and the double-disk molded ZnO in Fig. 6(a). The bloom shape is made out little wafers that are enclosed by an empty hexagonal ZnO. A hexagonal nut structure delineated in Fig. 6(c) is the base to shape bloom-like structures. Kumar *et al*. (2020) developed an innovative idea to grow ultrathin ZnO nanoflakes to prepare a tip based tool by hydrothermal assisted electrochemical discharge deposition process. In the same way researchers are developing hybrid process in corporation with hydrothermal process for better morphologies of ZnO NSs.

4. Hydrothermal synthesis using microwaves

Another technique for creation of NSs which is accepting a considerable measure of intrigue of late is the utilization of microwave warming instead of regular warming. Utilization of microwaves based heating for amalgamation provides basis for synthesizing ZnO NSs in field of high performance nanostructured materials for varied applications (Li *et al.* 2018, Pimentel *et al.* 2017, Thamima and Karuppuchamy 2015, Kang and Kim 2016). Zhu *et al*. (2011) effectively incorporated ZnO rod-amassed microspheres by means of a basic microwave-helped aqueous strategy. The as-arranged ZnO structures have astounding optical features and high photocatalytic action than conventional ZnO for deployment of MB under UV illumination, which can be ascribed to basic contrast, considering morphology, surface features and surface imperfections. The utilization of microwave aqueous amalgamation in modern situations may constitute an imperative commitment to the improvement of a green chemistry idea in industrial blend technology (Schmidt *et al.* 2015). Witkowski *et al*. (2018) integrated all around adjusted ZnO nano/microrods with indistinguishable crystallographic introduction on a c-plane GaN template, utilizing a microwave-assisted aqueous technique at 50°C for term of 2 minutes. In the meantime, this technique empowers a more prominent level of control over the diameter and thickness of the NRs. Two-dimensional ZnO nanosheets and one-dimensional dribble pipe-like, baseball bat-like, gear-like, bud-like, grenade-like, prism-like, bamboo-like, brush-like, arrow-like, pencil-like, strolling stick-like, taper-like, shuttle-like, and hollow pinnacle-like ZnO nanorods with different tips were combined by a basic hydrothermal course from the system of $\{CO(NH_2)^{2-}N_2H_4\}$ (Duo *et al.* 2017). Liang *et al*. (2014) detailed a clear, single-step, microwave-aided hydrothermal technique to create ZnO NSs with inconsistent morphologies. Balancing

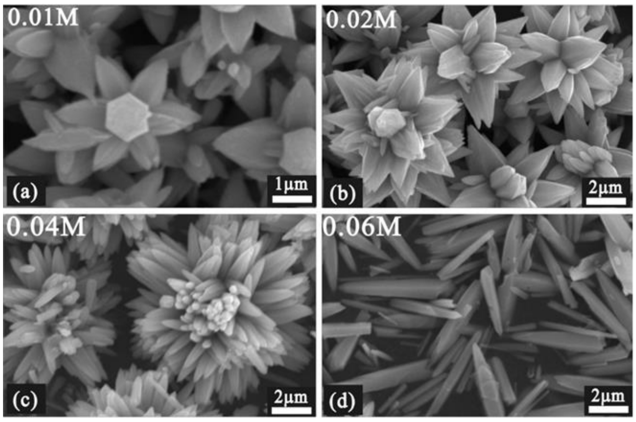


Fig. 7 Impact of [Zn^{2+}] on grown ZnO nanostructures (a) 0.01, (b) 0.02, (c) 0.04 and (d) 0.06 M (Liang *et al.* 2014)

of [Zn^{2+}] in solution precursors with no auxiliaries will allow to create urchin-shaped, blossom-shape, seven-spine and rod-like ZnO. Samples of ZnO were furthermore organized with contrasting [Zn^{2+}] under a similar microwave illumination situation as represented in Fig.7. The great command of the MAH amalgamation parameters similar to time, temperature and solvent of amalgamation response kept the primary ZnO hexagonal wurtzite stage. In any case, the concentration of Zn precursor as well as solvent time and amalgamation temperature influence the morphological structure creating rounded plates, producing plates, brush-like and 3D blossoms (Byzynski *et al.* 2018). Caglar *et al.* (2015) explored that in the microwave-helped hydrothermal strategy illumination time influenced the diameter of nanorods and orientation degree, pH value totally changed the molecule size and shape. The nanorods at first glance vanished after a little measure of decreasing in pH esteem. The adjustments in stoichiometry connection amongst Zn^{2+} and OH^- directly influence the morphology of the final structures (Barreto *et al.* 2015).

5. Doping of ZnO NSs

For controlling properties like band gap, ferromagnetism and electrical conductivity, some essential steps have to be taken in the form of doping of semiconducting nanostructured materials (Ahmad *et al*. 2020). A great deal of enthusiasm from analysts for conceivable applications in optics, electronics and visible light photocatalysis are produced by doping of transition metal of II-VI and III-V categories (Yu *et al*. 2016). Remarkable works have been done by the researchers in the field of doping of ZnO single crystal and thin films by transition metal (Poornaprakash *et al*. 2017, Samadi *et al*. 2016, Wu *et al*. 2013, Zhu *et al*. 2020). To enhance photocatalytic movement, ZnO nanowires were altered by Co^{2+} doping and CuS was coupling by means of a progression of advantageous hydrochemical reactions. In any case, a couple of reports on the blend and portrayal of doped ZnO NSs with various dopants like Co, Al, Mn, Ga, Cu, Sb, and so forth are accessible in the literature (Chow *et al*. 2013, Lavand and Malghe 2015, Lv *et al*. 2018, Mittal *et al*. 2014). The measure of doping is a conspicuous factor for fitting the properties of the NSs, there must be a conceivable method to control the morphology and doping fixation (Das *et al*. 2017). Hwang *et al*. (2014) control the morphology and doping centralization of P-doped ZnO NSs sequentially framed on the top sides of undoped ZnO NRs by means of aqueous technique. Ajala *et al*. (2018) reasoned that, to the extent the optoelectronic highlights are concerned, Al doping initiated a blue move of the band gap and a cathodic move of the quasi Fermi level. Notwithstanding, as the degree of these adjustments was too low, it was inferred that the optoelectronic highlights did not assume a huge part in the upgraded photocatalytic action of the powders. Then again, the nearness of surface defectivity initiates high water fondness of the Al adjusted samples. Mendez *et al*. (2018) arranged the C-doped photoactive circular TiO_2 and ZnO semiconductors by microwave-helped solvothermal amalgamation. They prepared two C-doped TiO_2 and ZnO tests with an unmistakable red-move in the vitality band gap of the semiconductors, essentially in TiO_2 based materials. Literature inferred that fitting of the crystalline stage, morphology, and porosity qualities can be accomplished by microwave-helped blend and consequently, this system is a promising outline device for the planning of C-doped mesopore photoactive semiconductors with a blend of anatase and rutile stages. An easy citric acid-mediated aqueous course has been utilized for blend of Eu-doped bloom-like ZnO progressive structures by Sin and Lam (2016). Sathya and Pushpanathan (2017) effectively arranged Pb doped ZnO semiconductor nanoparticles by the straightforward chemical precipitation technique. XRD examination affirmed that the crystallite size expands persistently to 10 (wt%). SEM outcomes affirmed the microstructural change from nanoparticle to rod-like microstructure on 10 (wt.%) Pb dopant. The aqueous synthesis of undecorated and Ag improved ZnO nanorods were accounted for by Wei *et al*. (2017). Byun *et al*. (2017) revealed that titanate NSs doped with Nb having upgraded photocatalytic movement under visible light illumination were effectively integrated by an aqueous procedure utilizing TiO_2 and Nb_2O_5 powders. Blended Nb-doped titanate NSs were made out of nanotubes, nanosheets, and TiO_2 NPs. They had organized a structure, with TiO_2 NPs at the center site, and titanate NSs went head to head with bordering titanate NSs. The fluorescence discharge is likewise adjusted upon gallium doping prompting an adjustment in the relative power, which persists for higher measures of dopant (Bernardo *et al*. 2017). The Room temperature ferromagnetism (RTFM) with upgraded polarization and coercivity in the Tb and co-doped ZnO nanoparticles were accounted for by Das *et al*. (2018). Chen *et al*. (2016) detailed that the gas detecting features of silver-doped sensors were great astounding than unadulterated, and the sensor of 1.0 wt% silver-doped ZnO ocean urchin-like NSs demonstrated the most raised response to ethanol with bring down fixation of 10 ppm at 260°C. The reasons were that ocean urchin-like structure could give broad specific surface locale and the doping extended flaws at first glance, both of them could assemble the consumed oxygen species.

Fig. 8 Utilization range of ZnO NSs materials

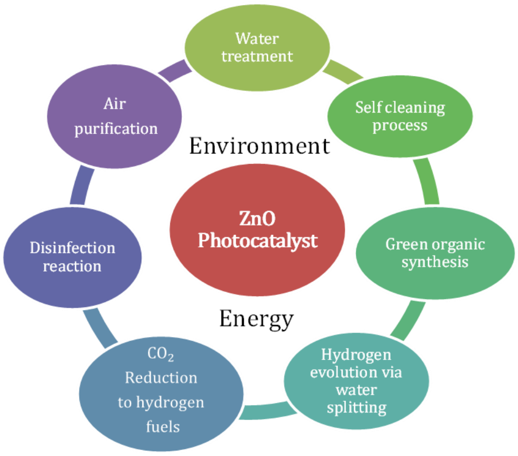


Fig. 9 Major fields for utilization of ZnO photocatalyst

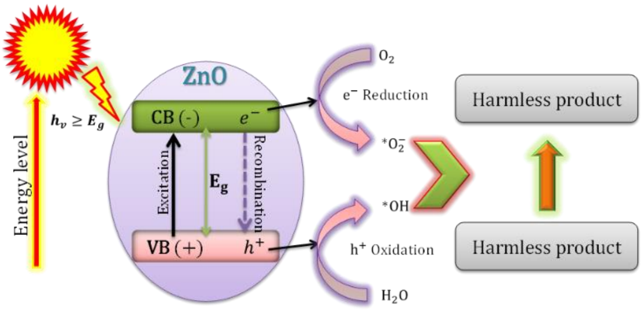


Fig. 10 Basic mechanism of ZnO photocatalysis for degradation of harmful productt

6. Potential applications

Different applications based on the ZnO hierarchical architectures are photocatalysis, field emission, electro-chemical sensors, supercapacitors, antibacterial agent and electrodes for lithium ion batteries (Manzano *et al*. 2011, Panda and Tseng 2013, Poongodi *et al*. 2015, Wang *et al*. 2015).

Various morphologies of ZnO NSs possess novel benefits of large surface area, permeable designs, and interdependent associations of the comprised nano-sized parts. Subsequently, ZnO NSs have tailored chemical and physical features, which are profoundly required for diverse applications (Hahn 2011, Qi *et al*. 2017, Weldegebrieal 2020). Following are the most prominent regions where ZnO NSs are exceptionally consolidated as portrayed in Fig.8. The detailed description of significant application fields with examples are discussed in this section.

6.1 Photocatalysis

Catalysis are consider as a significant tool in reducing harmful products arises from industries like refinery, food, petrochemical, and environment pollution (Goktas and Goktas 2021, Samadi *et al*. 2016). Photo-irradiation under UV visible source is the prime solution to expand the pace of photocatalysis process along with specific semiconductor photocatalyst under specific circumstances. Different application fields such as green organic synthesis, air and water treatment, renewable energy, CO_2 reduction and self-cleansing phenomenon are using ZnO photocatalyst for better outcome (Wang *et al*. 2018). A pictorial representation of potential application of ZnO photo-catalysts are outlined in Fig. 9 and the overall process of ZnO photocatalysis phenomenon for photocatalytic degradation of harmful products is shown in Fig. 10.

Photocatalytic phenomenon in ZnO occurs as absorption of photon energy (hυ) radiated from light source that has to be equivalent to or greater than the band gap energy of ZnO i.e., ($h\upsilon \geq E_g$). Absorption of photon energy produces excited state in the valence band (VB) and allows transfer of electrons (e^-) towards conduction band (CB) i.e., (e^-_{CB}) which prompt creation of holes (h^+) inside the VB i.e., (h^+_{VB}). The detachment and movement of charges ($e^-$and h^+) to the ZnO surface are the subsequent phenomenon. The reduction of quantum heed produces by recombination of holes and electrons which may happen by dissipation of photon energy for the photocatalytic phenomenon. The rate of recombination is unequivocally impacted by different factors with connection to the type of ZnO NSs (Byzynski *et al*. 2018, Ong *et al*. 2018, Pung *et al*. 2012). The exceptionally responsive holes and electrons at the outside of ZnO photocatalyst will in general cause oxidation and reduction reaction to produce hydroxyl revolutionaries (*OH) and superoxide anion extremists ($* O_2^-$), separately. The base level of the potential of CB in ZnO (-0.5 V) is more negative than the redox potential of $O_2/* O_2^-$ i.e., 0.33 V. In this manner, superoxide anion revolutionaries can be delivered by electrons. Interestingly, the highest point potential of the VB (+2.7 V) is more certain than the redox potential of $*OH/H_2O$ (+2.53 V) thus, hydroxyl radicals were form due to oxidation of H_2O molecules by holes.

6.2 Field emission

These devices exhibits various benefits, like low power utilization, protection from vacillation of temperature and radiation, less thermionic commotion, less dissipation of energy, micro-sized and nonlinearity, and remarkable characteristic of current and voltage behavior which shows significant variation of emission current at low voltage changes (Cheng *et al*. 2015, Wang *et al*. 2017). ZnO NSs incorporated in field emission were studied by Umar *et al*. (2016) and reported the growth of ZnO nanoflowers by thermal evaporation on Si-substrate and concluded that incorporation of ZnO NSs shows efficient field emission properties for device applications. Several researches were performed to assess the feasibility of different morphology of ZnO NSs on field emission devices and it was revealed that the development of ZnO NSs causing the great emission properties and promoting connection with integrated circuits as well as vacuum device applications (Dantas *et al*. 2020, Hahn 2011, Kumar *et al*. 2018).

6.3 Sensors

Industries like biotechnology, food processing and pharmaceutical sciences requires nonstop observation of biological phenomenon occurring during biological reactions. In such manner the growth of different sensors such as electrochemical sensors exhibit novel benefits such as large detection span, quick response, continuous observation, controlled manufacturing at less capital and reproducibility (Noah 2020). In these devices concepts of electro-analytical processes are used which provides quality investigation and sensing under the variation of potential and their resulting current. There are various techniques such as linear scan voltammograms and electrochemical impedance spectroscopic techniques which are used for efficient application of ZnO based sensors in biological applications (Shetti *et al*. 2019). Doped-ZnO hybrid sensors have high sensitivity and reproducibility which are used for gas sensing applications and also applied in biomedical industries (Ekrami *et al*. 2018, Li *et al*. 2020, Ren *et al*. 2020).

6.4 Lithium ion batteries

In the present scenario of increasing populace and industries, demand of high energy and climate balance for sustainable environment is becomes a big challenge for researchers. Thus they are investigating the development of renewable energy source and their conversion and storage systems also (Theerthagiri *et al*. 2019). ZnO NSs materials are now a days very promising materials for energy storage application such as batteries (Laurenti *et al*. 2015). Li-ion batteries are perhaps the main energy storage system which overcome the problems of electronic industries and furthermore have application in hybrid vehicles. Materials for high performance electrodes are prominent active material which influence the overall response of the batteries thus the development of electrode materials are again a challenging task for researchers (Liu *et al*. 2020, Xiao *et al*. 2018). ZnO NSs and doped ZnO NSs electrode materials are promising materials for high performance electrodes because of great optoelectronic properties, low cost, nontoxic and abundance. On a basic level, the response among lithium and ZnO anodes happens under the purported system of “conversion phenomenon” (Yuan *et al*. 2018). In the process of lithiation, the ZnO anode produces Li2O by conversion reaction implanted with nanosized metallic zinc groups (Wang *et al*. 2020).

6.5 Antibacterial application

The high biocompatibility and magnificent antimicrobial features of ZnO declare it as a prominent antibacterial agent (Sirelkhatim *et al*. 2015). Especially, ZnO NSs exhibits better results of the antibacterial application on Gram-negative and positive bacteria (Yusof *et al*. 2019). Nonetheless, the exact study of antibacterial phenomenon of ZnO is still under process, in this way confining the complete utilization of ZnO as an antibacterial material (Jiang *et al*. 2020). Recent and upcoming examinations on ZnO NSs based antibacterial system provides the basis for specific application on antibacterial work, but in future ZnO can be a promising agent for clinical usage after upgrading the investigations and overcoming the challenges.

6.6 Supercapacitors

Another class of energy storage device is “supercapacitors” which possesses high importance in view of its rate of quick charging and discharging, high service span and high capacity of power. Due to these features supercapactiros are mostly sued for backup source of energy, emergency source of energy and hybrid transport systems (Samuel *et al*. 2019). Nano-sized particles available in the nanocomposite materials are responsible for low ionic dissemination and less transfer of energy which is very much required to produce supercapacitors (Fávero *et al*. 2018). Nanocomposite materials having high specific capacitance value and service span are broadly utilized for developing supercapacitors. Yun *et al*. (2021) reported electrospinning technique to develop ZnMn2O4 electrode having one dimensional hollow NSs which produces high crystallinity. The developed electrode shows 100.8% of capacitance retention which is a remarkable cycle performance for different electronic systems. Guerra *et al*. (2019) fabricated ZnO coated carbon nanomaterial to develop an electrode for supercapacitor using laser technique. The finding of their experiments reveals that the electrodes are independent of thickness of deposited ZnO but ZnO film improves the specific capacitance and retention values which provides basis to use ZnO as a low cost potential material for supercapacitors.

6.7 High performance composite materials

Researches are going on to implement such distinguished properties of ZnO NSs into the field of high performance composite materials. Some of the prominent applications of such composites are in aviation industries due to improved mechanical properties especially impact strength (Kong *et al*. 2015). Continuous improvements of such materials will take the materials applications into different level such as in robotics and artificial intelligence, sensors and biomaterials, micro-electronics and photonics and defense and artillery (Wang *et al*. 2017). Recent advancements in the fabrication of ZnO NSs on the WCF lead towards the numerous applications in comparison to the natural carbon fibres (Ehlert *et al*. 2013, Zheng *et al*. 2016) more advanced development status compared to

Table 2 Application area of polymer based nanocomposites

Nano composites	Applications
Polyimide/SiO_2	Microelectronics
Polycaprolactone/SiO_2	Bone-bioerodible for skeletal tissue repair
Polyethylacrylate/SiO_2	Catalysis support, stationary phase for chromatography
PMMA/SiO_2	Dental application, optical devices
Poly(amide-imide) / TiO_2	Composite membranes for gas separation applications
Polycarbonate/SiO_2	Abrasion resistant coating
Shape memory polymers/SiC	Medical devices for gripping or releasing therapeutics within blood vessels
Poly(p-phenylene vinylene)/SiO_2	Non-liner optical material for optical waveguides
poly(3,4-ethylene-dioxythiophene)/V_2O_5	Cathode materials for rechargeable lithium batteries
PEO/LS	Airplane interiors, fuel tanks, components in electrical and electronic parts, brakes and tires
Nylon-6/LS	Automotive timing-belt – TOYOTA
PET/clay	Food packaging applications. Specific examples include packaging for processed meats, cheese, confectionery, cereals and boil-in-the-bag foods, fruit juice and dairy products, beer and carbonated drinks bottles
PLA/LS	Lithium battery development
Polyimide/clay	Automotive step assists - GM Safari and Astra Vans
SPEEK/laponite	Direct methanol fuel cells
Epoxy/MMT	Materials for electronics
Thermoplastic olefin/clay	Beverage container applications

metal and ceramic counterparts, in addition to their unique properties (Moussa *et al*. 2016, Velayutham *et al*. 2012). Application ranges of polymer nanocomposites are represented in Table 2. As it can be clearly discovered, the prominent usages of nanocomposites are huge, consisting of evolution of advance materials and the quality advancement of regarded components like sensors, cells and depositions. Still there is least application of nanocomposites in industries but advancements of these material from research to industry is growing and in coming few years it is expected to be extensive.

7. Summary and future perspective

The blend of ZnO NSs and their potential usage are checked on as far as development strategy, qualities, and utilities. The zinc oxide has an incredible variety in underlying morphology, most likely the most extravagant group of NSs among all materials, which subsequently lead the distribution of thousands of literatures and patents. The utilizations of ZnO NSs incorporate field-effect semiconductors, field-emission devices, piezoelectric nanogenerators, biosensors, p-n heterojunction diodes and photovoltaic cells. A minimal cost and simple method should be created by which a uniquely needed shape of NSs can be incorporated. Particularly, the designing and specific developments of ZnO NSs on wanted destinations are needed for the nanodevices creations and incorporations. The most promising quality of 3D ZnO nanostructured material is large surface area with porous structure, and enables more than one chemical and physical process. Additionally, nanostructured materials allow tailored properties of each nanostructure and also create advance features because of in-between relation of each nanostructure. Hence 3D nanostructured materials allow a wide variety of utility. ZnO NSs grown on WCF also have potential to use as hybrid nano-composites incorporation with the suitable matrix medium. ZnO NSs-WCF-epoxy hybrid composites have great potential to replace existing unreinforced materials in industries like aerospace, petrochemical and automobiles. Tailored properties like high impact strength, wear resistant, corrosion resistant and low friction coefficient allow these materials to become prominent choice in various technological utilities. ZnO keeps on being seriously concentrated because of its special and complex properties, just as incredible potential for an assortment of pragmatic applications. Despite various investigations in the literatures, few significant issues stay uncertain which need to be studied, as summarized in Fig. 11.

There has been loads of progress in development of ZnO NSs and their utilization for an assortment of useful applications. Eventually, the reproducibility and dependability of the acquired outcomes (particularly on account of doping of ZnO) stays a huge concern. A significant issue which should be defeated to tackle this issue is the explanation of the connection between development conditions, types and groupings of imperfection framed, and properties estimated. Additionally, there is significant interest in the advancement of surface change or passivation agents which could bring about the decrease of imperfection emission, solid and stable electronic features, improved charge transport, and device execution. Because of huge surface-to-volume proportions of the n NSs, surface nature of the material assumes an essential part in deciding its general conduct and a huge change in the material properties can be accomplished with appropriately planned surface adjustments. It is additionally important to examine significant issues of harmfulness and ecotoxicity of ZnO NSs. For instance, in reports worried about the optical or electronic properties of ZnO and its applications in electronic or optoelectronic appliances, ZnO is much of the time depicted as a non-harmful or even biocompatible material. However, various investigations show that ZnO displays huge ecotoxicity to a wide range of organic entities. This should be considered in the uses of this material, with the goal that guidelines concerning its removal to forestall uncontrolled delivery into the climate could be set up. Besides, most of ecotoxicity considers have been performed on uncovered nanomaterials. In existing applications, for example, sunscreens, nanoparticles as a rule have altered surfaces. Surface alterations as examined

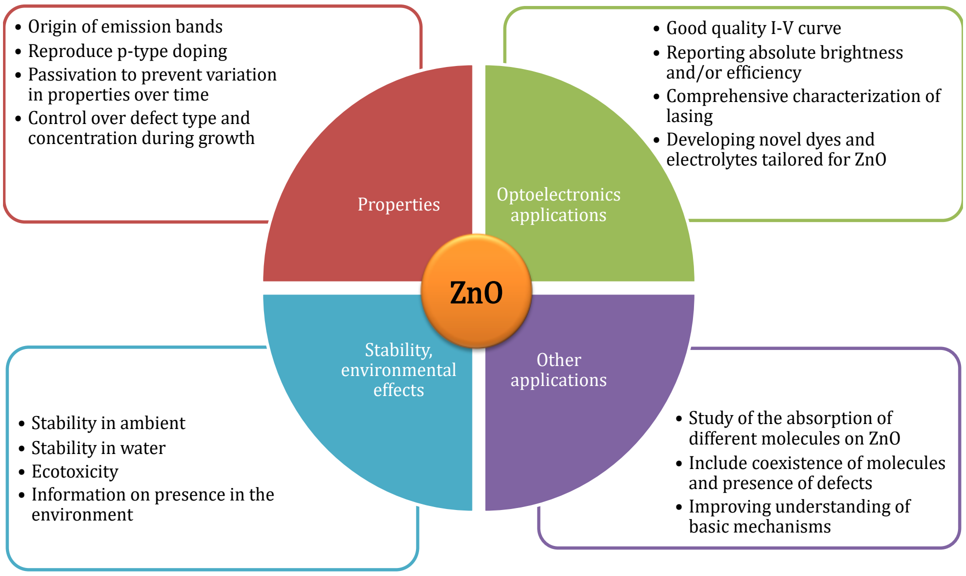


Fig. 11 Current research situation and challenges for ZnO NSs materials

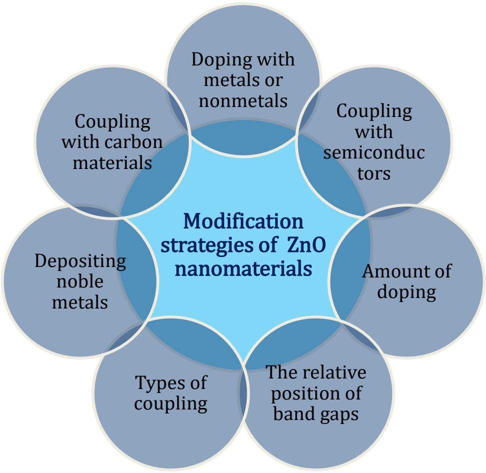


Fig. 12 Strategies to modify ZnO nanomaterials for better outcomes

above will likewise be alluring for optoelectronic and electronic gadget applications. Hence, there is a conspicuous and pressing requirement for considering the impact of surface alterations on the harmfulness of ZnO NSs.

For the treatment of waste water, ZnO NSs are reasonable photocatalyst to remove azo dyes dissolved in waste water. ZnO based photocatalysts are very popular because of its high UV-photoactive, economical, stability and chemically and naturally inert. Notwithstanding, the response of ZnO catalyst is restricted due to variable like insensitivity in visible region due to wide band gap, less photonic efficiency due to quick recombination of holes and electrons, and corrosive disintegration. To overcome these issues, doping of the nanomaterial and hybrid material formation is required. Thus altered ZnO nanomaterials based photocatalysts are the required solution for successful treatment of azo dye in waste water treatment and removal harmful substance from any surface. Scientists have utilized different techniques to enhance the properties of ZnO NSs photocatalyst for effective removal of organic toxins as portrayed in Fig. 12. Doping of ZnO exhibits morphological variation, crystal imperfections such as dislocation and deformation. With the aid of required doping agent in adequate amount these defects of ZnO crystals can significantly upgrade the photocatalytic phenomenon. It was noted that, the amount of doping agent is a vital parameter to enhance the visible range photocatalytic action that relies upon synthesis technique and size of the doping agent (Chen *et al*. 2020). Metallic dopants produces another energy band level but do not alter location of CB and VB of ZnO and this intra energy band is required for certain uses like creation of large oxidant holes. But, nonmetallic dopant increases VB level of ZnO and exhibits decrement in band gap. Corrosion of ZnO under photon energy is a significant problem which can be resolve by the metallic dopant. Metal dopant also causes reduction in ZnO growth thus the small crystals having large surface area is produces. On the basis of exploratory and hypothetical outcomes, doped ZnO photocatalyst is perceived as a fitting technique to upgrade photocatalytic action (Deng *et al*. 2020). But still there are some prominent concerns which are affecting the photocatalytic utilizations. Following are some major issues:

a. Survey of literatures exhibits that mostly doped ZnO were used for removal of harmful substances such as dye, thus detailed analysis of fragmentation and photo degradation of pollutants.

b. Detailed study of antibacterial phenomenon of pollutants and their detoxification ought to be also performing on ZnO photocatalysts.

c. Limited study is available for oxidization of volatile matter by photocatalysis and lack of study on purification of indoor and outside air by ZnO photocatalysts.

Enhancement in the available ZnO nanostructured materials allow researchers to implement those materials into the diverse electronic applications due to their enhancement in absorption range, stability, sensitivity, crystallinity of ZnO and many more. Notwithstanding these noteworthy improvements, still few difficulties are remains unsolved.

a. Irrespective of the improved synthesis techniques for controlled growth of ZnO NSs and their 3D hierarchical composites, enhancement in the quantification of scale and size of NSs and their reproducibility are still unsolved issue. Since there are lots of ongoing researchers showing the impact of varied morphologies and synthesis mechanism so which shows further scope to investigate the novel features of ZnO based on their synthesis, applications, shape, size and structure.

b. Apart from ZnO hierarchical structure, the execution of electronic systems also relies upon concentration, dimensions and imperfections in NSs. Incorporating 3D ZnO NSs having controlled geometry and chemical stability will further quantify the properties of resulting materials.

c. Study of real time application of ZnO NSs and their variations due to dynamic factors will also provide basis to improve the overall performance by understanding and resolving the real-time issues.

d. Due to limited availability on high performance ZnO NSs/heterojunction development strategies, devices are not economical and efficient. Thus further investigations are needed to implement current development in the nanoscience to develop novel devices.

e. To resolve the issue of low effectiveness and durability of ZnO based devices, further study of ZnO catalysts are needed. Also practical difficulty in terms of sensitivity and effectiveness provides basis for the researchers to developed advance hybrid materials based on ZnO NSs using novel strategies of doping and synthesis.

f. Different analytical tools and software should be used to assess the real time situation of the fabricated ZnO NSs electronic devices.

g. Development of optimum designs of electronic devices by mathematical and logical computations is needed for economically feasible large scale heterojunction semiconductors.

h. It is profoundly imperative to develop beneficial and reformist nanomaterials to set up the ZnO NSs heterojunction for sensible usage and their commercialization.

Extensive studies on WCF grafted with ZnO NSs is primarily rely upon micro fibre tows or woven preforms, the nanostructure synthesis technique requires to be scaled up to manufacture continuous nanostructured WCF, So that these grafter WCF will allow fabrication of hybrid composites tapes/pre-pregs and composite to assess mechanical properties via compression, shear, impact and delamination testing. Tailored properties variation due to NSs of resulting composites need to be assessed by open hole compression and compression after impact. In the long run, the fabrication and characterization of hybrid composites structures simultaneously grown on the fibres and spreading in the matrix may be possible, permitting even better service conditions. The development in the field of ZnO nanostructured hybrid composites reveals that, in coming years ZnO assisted advanced material must be pioneer material for aviation and industrial usage. Various studies and researches on hybrid composites are still going on but reflect huge promise for large scale production of nanostructured composites. The accompanying comments were extracted in the view of thorough study of literatures based on ZnO/polymer nanocomposite which exhibit the current difficulties in nanocomposite.

i. Overall features of the nanocomposite greatly rely on the interface parameter between the polymetric matrix and ZnO NSs. Surface modification is one of the best suited technique for enhancing the interfacial strength and modulus of the nanocomposites. Current situation of interaction between matrix and reinforcement is only based on ZnO NSs containing polar groups which can be further improve by aiding more surface modification techniques.

ii. The dispersion of NSs into the matrix is one of the deciding factors for properties of the resulting composites. Thus appropriate method of fabrication must be used for optimum dispersion of ZnO NSs into the polymer matrix with uniform material properties and light weight. Current fabrication techniques also require further modification so that final composite can contain desirable outcomes.

iii. Dielectric properties of the composite materials can be tuned by adding ZnO NSs into matrix even at low concentration because polar group present in the ZnO surface cause reduction of surface charge of the composites.

iv. Detailed study of interfacial interaction of ZnO NSs and polymer matrix by different analysis software or simulation technique is much needed to assess the real time application behavior of resulting nanocomposite.

v. High performance ZnO nanostructured composite materials which are compatible with the sensors to measure the failure mechanism are expected. ZnO nanomaterial composites are favorable for device applications and biomedical area but least possible weight and toxicity are also deciding parameters for commercialization of material for mankind.

Numerous categories of NSs improvised matrix products are now conventionally used including nanostructured epoxy resins, prepregs and sizings, which will propagate the production of large scale nanostructured composites. Additionally the excellent thermal and electrical conductivity of ZnO NSs should enable nanostructured hybrid composites to become new era of multifunctional materials. Currently Preparation of functional and structural hierarchical composites having distinguished performance characteristics is under development. This can be concluded that more application range of nanostructured hybrid composites will come in knowledge in few years.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Abdelfatah, M. and El-Shaer, A. (2018), “One step to fabricate vertical submicron ZnO rod arrays by hydrothermal method without seed layer for optoelectronic devices”, *Mater. Lett.*, **210**, 366-369. https://doi.org/10.1016/j.matlet.2017.09.064.

Absalan, H. and Ghodsi, F.E. (2012), “Comparative study of ZnO thin films prepared by different sol-gel route”, *Iran. J. Phys. Res.*, **11**(4),

Ahmad, M., Ahmad, M.K., Nafarizal, N., Soon, C.F., Suriani, A.B., Mohamed, A. and Mamat, M.H. (2020), “Chemisorbed CO2 molecules on ZnO nanowires (100 nm) surface leading towards enhanced piezoelectric voltage”, *Vacuum.* **182**, 109565. https://doi.org/10.1016/j.vacuum.2020.109565.

Ajala, F., Hamrouni, A., Houas, A., Lachheb, H., Megna, B., Palmisano, L. and Parrino, F. (2018), “The influence of Al doping on the photocatalytic activity of nanostructured ZnO: The role of adsorbed water”, *Appl. Surf. Sci.*, **445**, 376-382. https://doi.org/10.1016/j.apsusc.2018.03.141.

Al-Ruqeishi, M.S., Mohiuddin, T., Al-Habsi, B., Al-Ruqeishi, F., Al-Fahdi, A. and Al-Khusaibi, A. (2019), “Piezoelectric nanogenerator based on ZnO nanorods”. *Arab. J. Chem.*, **12**(8), 5173-5179. https://doi.org/10.1016/j.arabjc.2016.12.010.

Amin, G., Asif, M.H., Zainelabdin, A., Zaman, S., Nur, O. and Willander, M. (2011), “Influence of pH, precursor concentration, growth time and temperature on the morphology of ZnO nanostructures grown by the hydrothermal method”, *J. Nanomater.*, **2011**. https://doi.org/10.1155/2011/269692.

Barreto, G., Morales, G., Cañizo, A. and Eyler, N. (2015), “Microwave assisted synthesis of ZnO tridimensional nanostructures”, *Procedia Mater. Sci.*, **8**, 535-540. https://doi.org/10.1016/j.mspro.2015.04.106.

Baruah, S. and Dutta, J. (2009), “Hydrothermal growth of ZnO nanostructures”, *Sci. Technol. Adv. Mat.*, **10**(1), https://doi.org/10.1088/1468-6996/10/1/013001.

Baruwati, B., Kumar, D.K. and Manorama, S.V. (2006), “Hydrothermal synthesis of highly crystalline ZnO nanoparticles: A competitive sensor for LPG and EtOH”, *Sensor Actuat. B Chem.*, **119**(2), 676-682. https://doi.org/10.1016/j.snb.2006.01.028.

Bernardo, M.S., Villanueva, P.G., Jardiel, T., Calatayud, D.G., Peiteado, M. and Caballero, A.C. (2017), “Ga-doped ZnO self-assembled nanostructures obtained by microwave-assisted hydrothermal synthesis: Effect on morphology and optical properties”, *J. Alloy Compd.*, **722**, 920-927. https://doi.org/10.1016/j.jallcom.2017.06.160.

Bhattacharyya, P., Agarwal, B., Goswami, M., Maiti, D., Baruah, S. and Tribedi, P. (2017), “Zinc oxide nanoparticle inhibits the biofilm formation of Streptococcus pneumoniae”, *Antonie van Leeuwenhoek*, **111**(1), 89-99. https://doi.org/10.1007/s10482-017-0930-7.

Boro, B., Gogoi, B., Rajbongshi, B. M. and Ramchiary, A. (2018), “Nano-structured TiO2/ZnO nanocomposite for dye-sensitized solar cells application: A review”, *Renew. Sust. Energ. Rev.*, **81**, 2264-2270. https://doi.org/10.1016/j.rser.2017.06.035

Brintha, S.R. and Ajitha, M. (2015), “Synthesis and characterization of ZnO nanoparticles via aqueous solution, sol-gel and hydrothermal methods”, *IOSR J. Appl. Chem.*, **8**(11), 66-72. https://doi.org/10.9790/5736-081116672.

Byun, J.M., Choi, H.R., Kim, Y. Do, Sekino, T. and Kim, S.H. (2017), “Photocatalytic activity under UV/Visible light range of Nb-doped titanate nanostructures synthesized with Nb oxide”, *Appl. Surf. Sci.*, **415**, 126-131. https://doi.org/10.1016/j.apsusc.2016.08.132.

Byzynski, G., Pereira, A.P., Volanti, D.P., Ribeiro, C. and Longo, E. (2018), “High-performance ultraviolet-visible driven ZnO morphologies photocatalyst obtained by microwave-assisted hydrothermal method”, *J. Photoch. Photobio. A*, **353**, 358-367. https://doi.org/10.1016/j.jphotochem.2017.11.032.

Caglar, Y., Gorgun, K. and Aksoy, S. (2015), “Effect of deposition parameters on the structural properties of ZnO nanopowders prepared by microwave-assisted hydrothermal synthesis”, *Spectrochim. Acta A*, **138**, 617-622. https://doi.org/10.1016/j.saa.2014.12.008.

Chen, H., Ma, S.Y., Jiao, H.Y., Yang, G.J., Xu, X.L., Wang, T.T., Jiang, X.H. and Zhang, Z.Y. (2016), “The effect microstructure on the gas properties of Ag doped zinc oxide sensors: Spheres and sea-urchin-like nanostructures”, *J. Alloy Compd.*, **687**, 342-351. https://doi.org/10.1016/j.jallcom.2016.06.153.

Chen, Q., Sun, Y., Wang, Y., Cheng, H. and Wang, Q.M. (2013), “ZnO nanowires-polyimide nanocomposite piezoresistive strain sensor”, *Sensor Actuat. A Phys.*, **190**, 161-167. https://doi.org/10.1016/j.sna.2012.11.006.

Chen, Y., Wang, Y., Fang, J., Dai, B., Kou, J., Lu, C. and Zhao, Y. (2020), “Design of a ZnO/Poly(vinylidene fluoride) inverse opal film for photon localization-assisted full solar spectrum photocatalysis”, *Chinese J. Catal.*, **42**(1), 184-192. https://doi.org/10.1016/S1872-2067(20)63588-4.

Cheng, S., Hill, F.A., Heubel, E.V. and Velasquez-Garcia, L.F. (2015), “Low-bremsstrahlung X-ray source using a low-voltage high-current-density nanostructured field emission cathode and a transmission anode for markerless soft tissue imaging”, *J. Microelectromech. S.*, **24**(2), 373-383. https://doi.org/10.1109/JMEMS.2014.2332176.

Chow, L., Lupan, O., Chai, G., Khallaf, H., Ono, L.K., Roldan Cuenya, B., Tiginyanu, I.M., Ursaki, V.V., Sontea, V. and Schulte, A. (2013), “Synthesis and characterization of Cu-doped ZnO one-dimensional structures for miniaturized sensor applications with faster response”, *Sensor Actuat., A Phys.*, **189**, 399-408. https://doi.org/10.1016/j.sna.2012.09.006.

Dantas, M.O.S., Criado, D., Zúñiga, A., Silva, W.A.A., Galeazzo, E., Peres, H.E.M. and Kopelvski, M.M. (2020), “ZnO nanowire-based field emission devices through a microelectronic compatible route”, *J. Integr. Circuit Syst.*, **15**(1), 1-6. https://doi.org/10.29292/jics.v15i1.105.

Das, G., Deka, B.K., Lee, S.H., Park, Y. and Yoon, Y.S. (2015), “Poly (vinyl alcohol)/silica nanoparticles based anion-conducting nanocomposite membrane for fuel-cell applications”, *Macromol. Res.*, **23**(3), 256-264. https://doi.org/10.1007/s13233-015-3033-1.

Das, S., Bandyopadhyay, A., Das, S., Das, D. and Sutradhar, S. (2018), “Defect induced room-temperature ferromagnetism and enhanced dielectric property in nanocrystalline ZnO co-doped with Tb and Co”, *J. Alloy Compd.*, **731**, 591-599. https://doi.org/10.1016/j.jallcom.2017.10.057.

Das, S., Das, S. and Sutradhar, S. (2017), “Effect of Gd3+and Al3+on optical and dielectric properties of ZnO nanoparticle prepared by two-step hydrothermal method”, *Ceram. Int.*, **43**(9), 6932-6941. https://doi.org/10.1016/j.ceramint.2017.02.116.

Deka, B.K., Mandal, M. and Maji, T.K. (2012), “Effect of nanoparticles on flammability, UV resistance, biodegradability and chemical resistance of wood polymer nanocomposite”, *Ind. Eng. Chem. Res.*, **51**(37), 11881-11891. https://doi.org/10.1021/ie3003123.

Deka, B.K., Kong, K., Seo, J., Kim, D., Park, Y. Bin and Park, H.W. (2015), “Controlled growth of CuO nanowires on woven carbon fibers and effects on the mechanical properties of woven carbon fiber/polyester composites”, *Compos. Part A Appl. S.*, **69**, 56-63. https://doi.org/10.1016/j.compositesa.2014.11.001.

Deng, H., Xu, F., Cheng, B., Yu, J. and Ho, W. (2020), “Photocatalytic CO2 reduction of C/ZnO nanofibers enhanced by an Ni-NiS cocatalyst”, *Nanoscale*, **12**(13), 7206-7213. https://doi.org/10.1039/c9nr10451h.

Djurišić, A.B., Chen, X., Leung, Y.H. and Ng, A.M.C. (2012), “ZnO nanostructures: Growth, properties and applications”, *J. Mater. Chem.*, **22**(14), 6526-6535. https://doi.org/10.1039/c2jm15548f.

Duo, S., Li, Y., Liu, Z., Zhong, R., Liu, T. and Xu, H. (2017), “Preparation of ZnO from 2 D nanosheets to diverse 1 D nanorods and their structure, surface area, photocurrent, optical and photocatalytic properties by simple hydrothermal synthesis”, *J. Alloy Compd.*, **695**, 2563-2579. https://doi.org/10.1016/j.jallcom.2016.11.162.

Ehlert, G.J., Galan, U. and Sodano, H.A. (2013), “Role of surface chemistry in adhesion between ZnO nanowires and carbon fibers in hybrid composites”, *ACS Appl. Mater. Interf.*, https://doi.org/10.1021/am302060v.

Ekrami, M., Magna, G., Emam-Djomeh, Z., Yarmand, M.S., Paolesse, R. and Di Natale, C. (2018), “Porphyrin-functionalized zinc oxide nanostructures for sensor applications”, *Sensors*, **18**(7), 2279. https://doi.org/10.3390/s18072279.

Fan, J., Li, T. and Heng, H. (2014), “Hydrothermal growth and optical properties of ZnO nanoflowers”, *Mater. Res. Express*, **1**(4), 045024. https://doi.org/10.1088/2053-1591/1/4/045024.

Fávero, V.O., Oliveira, D.A., Lutkenhaus, J.L. and Siqueira, J.R. (2018), “Layer-by-layer nanostructured supercapacitor electrodes consisting of ZnO nanoparticles and multi-walled carbon nanotubes”, *J. Mater. Sci.*, **53**(9), 6719-6728. https://doi.org/10.1007/s10853-018-2010-4.

Foo, K.L., Hashim, U., Muhammad, K. and Voon, C.H. (2014), “Sol-gel synthesized zinc oxide nanorods and their structural and optical investigation for optoelectronic application”, *Nanosc. Res. Lett.*, **9**(1), 1-10. https://doi.org/10.1186/1556-276X-9-429.

Fujisawa, H., Kobayashi, C., Nakashima, S. and Shimizu, M. (2013), “Two-step growth of ZnO nanorods by using MOCVD and control of their diameters and surface densities”, *J. Korean Phys. Soc.*, **62**(8), 1164-1168. https://doi.org/10.3938/jkps.62.1164.

Ghasaban, S., Atai, M. and Imani, M. (2017), “Simple mass production of zinc oxide nanostructures via low-temperature hydrothermal synthesis”, *Mater. Res. Express*, **4**(3), https://doi.org/10.1088/2053-1591/aa5dcc.

Goktas, S. and Goktas, A. (2021), “A comparative study on recent progress in efficient ZnO based nanocomposite and heterojunction photocatalysts: A review”, *J. Alloy Compd.*, 158734. https://doi.org/10.1016/j.jallcom.2021.158734.

Gu, X., Li, C., Yuan, S., Ma, M., Qiang, Y. and Zhu, J. (2016), “ZnO based heterojunctions and their application in environmental photocatalysis”, *Nanotechnology*, **27**(40), 402001. https://doi.org/10.1088/0957-4484/27/40/402001.

Guerra, A., Achour, A., Vizireanu, S., Dinescu, G., Messaci, S., Hadjersi, T., Boukherroub, R., Coffinier, Y. and Pireaux, J.J. (2019), “ZnO/Carbon nanowalls shell/core nanostructures as electrodes for supercapacitors”, *Appl. Surf. Sci.*, **481**, 926-932. https://doi.org/10.1016/j.apsusc.2019.03.204.

Guo, H., Zhang, W., Sun, Y., Zhou, T., Qiu, Y., Xu, K., Zhang, B. and Yang, H. (2015), “Double disks shaped ZnO microstructures synthesized by one-step CTAB assisted hydrothermal methods”, *Ceram. Int.*, **41**. https://doi.org/10.1016/j.ceramint.2015.04.122.

Guo, X., Zhao, Q., Li, R., Pan, H., Guo, X., Yin, A. and Dai, W. (2010), “Synthesis of ZnO nanoflowers and their wettabilities and photocatalytic properties”, *Opt. Express*, **18**(17), 18401-18406. https://doi.org/10.1364/OE.18.018401.

Hahn, Y.B. (2011), “Zinc oxide nanostructures and their applications”, *Korean J. Chem. Eng.*, **28**(9), 1797-1813. https://doi.org/10.1007/s11814-011-0213-3.

Hasnidawani, J.N., Azlina, H.N., Norita, H., Bonnia, N.N., Ratim, S. and Ali, E.S. (2016), “Synthesis of ZnO nanostructures using sol-gel method”, *Procedia Chem.*, **19**, 211-216. https://doi.org/10.1016/j.proche.2016.03.095.

Hazarika, A., Deka, B.K., Kim, D.Y., Kong, K., Park, Y. Bin and Park, H.W. (2015), “Growth of aligned ZnO nanorods on woven Kevlar® fiber and its performance in woven Kevlar® fiber/polyester composites”, *Compos. Part A Appl S*, **78**, 284-293. https://doi.org/10.1016/j.compositesa.2015.08.022.

Henry, M., Jolivet, J.P. and Livage, J. (1992), “Aqueous chemistry of metal cations: Hydrolysis, condensation and complexation”, *Chem. Spectroscopy Application Sol Gel Glass*, 153-206. https://doi.org/10.1007/BFb0036968.

Hilgendorff, M. (1998), “From ZnO colloids to nanocrystalline highly conductive films”, *J. Electrochem. Soc.*, **145**(10), 3632. https://doi.org/10.1149/1.1838855.

Hong, S.H., Kim, M.H., Yun, H.W., Paik, T. and Lee, H. (2017), “Solution-processed fabrication of superhydrophobic hierarchical zinc oxide nanostructures via nanotransfer printing and hydrothermal growth”, *Surf. Coat. Tech.*, **331**, 189-195. https://doi.org/10.1016/j.surfcoat.2017.10.022.

Hou, Y., Soleimanpour, A.M. and Jayatissa, A.H. (2013), “Low resistive aluminum doped nanocrystalline zinc oxide for reducing gas sensor application via sol-gel process”, *Sensor Actuat. B Chem.*, **177**, 761-769. https://doi.org/10.1016/j.snb.2012.11.085.

Hsu, C.L. and Chang, S.J. (2014), “Doped ZnO 1D nanostructures: Synthesis, properties and photodetector application”, *Small*, **10**(22), 4562-4585. https://doi.org/10.1002/smll.201401580.

Hwang, S.H., Moon, K.J., Lee, T.Il, Lee, W. and Myoung, J.M. (2014), “Controlling phosphorus doping concentration in ZnO nanorods by low temperature hydrothermal method”, *Mater. Chem. Phys.*, **143**(2), 600-604. https://doi.org/10.1016/j.matchemphys.2013.09.038.

Jiang, S., Lin, K. and Cai, M. (2020), “ZnO Nanomaterials: Current advancements in antibacterial mechanisms and applications”, *Front. Chem.*, **8**, 580. https://doi.org/10.3389/fchem.2020.00580.

Jung, H.J., Lee, S., Yu, Y., Hong, S.M., Choi, H.C. and Choi, M.Y. (2012), “Low-temperature hydrothermal growth of ZnO nanorods on sol-gel prepared ZnO seed layers: Optimal growth conditions”, *Thin Solid Films*, **524**, 144-150. https://doi.org/10.1016/j.tsf.2012.10.007.

Zak, A.K., Majid, W.A., Abrishami, M.E. and Yousefi, R. (2011), “X-ray analysis of ZnO nanoparticles by Williamson-Hall and size-strain plot methods”, *Solid State Sci.*, **13**(1), 251-256. https://doi.org/10.1016/j.solidstatesciences.2010.11.024.

Ko, S.H., Lee, D., Kang, H.W., Nam, K.H., Yeo, J.Y., Hong, S.J., Grigoropoulos, C.P. and Sung, H.J. (2011), “Nanoforest of hydrothermally grown hierarchical ZnO nanowires for a high efficiency dye-sensitized solar cell”, *Nano Lett.*, **11**(2), 666-671. https://doi.org/10.1021/nl1037962.

Kong, K., Deka, B.K., Kwak, S.K., Oh, A., Kim, H., Park, Y.B and Park, H.W. (2013), “Processing and mechanical characterization of ZnO/polyester woven carbon-fiber composites with different ZnO concentrations", *Compos. Part A Appl. S*, **55**, 152-160. https://doi.org/10.1016/j.compositesa.2013.08.013.

Kong, K., Seo, J., Deka, B.K. and Park, H.W. (2015), "Experimental study for the improvement of the impact property of carbon fiber composites", *Trans. Korean Soc. Mech. Eng.*, 1641-1642.

Kozuka, Y., Tsukazaki, A. and Kawasaki, M. (2014), "Challenges and opportunities of ZnO-related single crystalline heterostructures". *Appl. Phys. Rev.*, **1**(1), 011303. https://doi.org/10.1063/1.4853535.

Król, A., Pomastowski, P., Rafińska, K., Railean-Plugaru, V. and Buszewski, B. (2017), "Zinc oxide nanoparticles: Synthesis, antiseptic activity and toxicity mechanism", *Adv. Colloid Interfac.*, 249, 37-52. https://doi.org/10.1016/j.cis.2017.07.033.

Kumar, D., Rai, R.S. and Singh, N.K. (2020), "An innovative approach to deposit ultrathin ZnO nanoflakes (2D) through hydrothermal assisted electrochemical discharge deposition and growth method", *Ceram. Int.*, **46**(16), 26216-26220. https://doi.org/10.1016/j.ceramint.2020.07.009.

Kumar, S.G. and Rao, K.S.R.K. (2015), "Zinc oxide based photocatalysis: Tailoring surface-bulk structure and related interfacial charge carrier dynamics for better environmental applications", *RSC Adv.*, **5**(5), 3306-3351. https://doi.org/10.1039/c4ra13299h.

Kumar, S., Sahare, P.D. and Kumar, S. (2018), "Optimization of the CVD parameters for ZnO nanorods growth: Its photoluminescence and field emission properties", *Mater. Res. Bull.* **105**, 237-245. https://doi.org/10.1016/j.materresbull.2018.05.002.

Kwak, G., Seol, M., Tak, Y. and Yong, K. (2009), "Superhydrophobic ZnO nanowire surface: Chemical modification and effects of UV irradiation", *J. Phys. Chem. C*, **113**(28), 12085-12089. https://doi.org/10.1021/jp900072s.

Laurenti, M., Garino, N., Porro, S., Fontana, M. and Gerbaldi, C. (2015), "Zinc oxide nanostructures by chemical vapour deposition as anodes for Li-ion batteries", *J. Alloy. Compd.*, **640**, 321-326. https://doi.org/10.1016/j.jallcom.2015.03.222.

Lavand, A.B. and Malghe, Y.S. (2015), "Synthesis, characterization and visible light photocatalytic activity of nitrogen-doped zinc oxide nanospheres", *J. Asian Ceram. Soc.*, **3**(3), 305-310. https://doi.org/10.1016/j.jascer.2015.06.002.

Li, G., Wu, Y., Hong, Y., Zhao, X., Reyes, P.I. and Lu, Y. (2020), "Magnesium zinc oxide nanostructure-modified multifunctional sensors for full-scale dynamic monitoring of pseudomonas aeruginosa biofilm formation", *ECS J. Solid State Sci. Technol.*, **9**(11), 115026. https://doi.org/10.1149/2162-8777/abb795.

Li, K., Zhou, X., Zhao, Z., Chen, C., Wang, C., Ren, B. and Zhang, L. (2018), "Synthesis of zirconium carbide whiskers by a combination of microwave hydrothermal and carbothermal reduction", *J. Solid State Chem.*, **258**, 383-390. https://doi.org/10.1016/j.jssc.2017.11.002.

Liang, S., Zhu, L., Gai, G., Yao, Y., Huang, J., Ji, X., Zhou, X., Zhang, D. and Zhang, P. (2014), "Synthesis of morphology-controlled ZnO microstructures via a microwave-assisted hydrothermal method and their gas-sensing property", *Ultrason. Sonochem.*, **21**(4), 1335-1342. https://doi.org/10.1016/j.ultsonch.2014.02.007.

Liang, Z., Cui, H., Wang, K., Yang, P., Zhang, L., Mai, W., Wang, C.-X. and Liu, P. (2012), "Morphology-controllable ZnOnanotubes and nanowires: synthesis, growth mechanism and hydrophobic property", *Cryst. Eng. Comm*, **14**(5), 1723-1728. https://doi.org/10.1039/C2CE06045K.

Liu, J., Wu, J., Zhou, C., Zhang, P., Guo, S., Li, S., Yang, Y., Li, K., Chen, L. and Wang, M. (2020), "Single-phase ZnCo2O4 derived ZnO-CoO mesoporous microspheres encapsulated by nitrogen-doped carbon shell as anode for high-performance lithium-ion batteries", *J. Alloy Compds.*, **825**, 153951. https://doi.org/10.1016/j.jallcom.2020.153951.

Liu, T., Li, Y., Zhang, H., Wang, M., Fei, X., Duo, S., Chen, Y., Pan, J. and Wang, W. (2015), "Tartaric acid assisted hydrothermal synthesis of different flower-like ZnO hierarchical architectures with tunable optical and oxygen vacancy-induced photocatalytic properties", *Appl. Surf. Sci.*, **357**, 516-529. https://doi.org/10.1016/j.apsusc.2015.09.031.

Luković Golić, D., Branković, G., Počuča Nešić, M., Vojisavljević, K., Rečnik, A., Daneu, N., Bernik, S., Šćepanović, M., Poleti, D. and Branković, Z. (2011), "Structural characterization of self-assembled ZnO nanoparticles obtained by the sol-gel method from $Zn(CH_3COO)_22H_2O$", *Nanotechnology.*, **22**(39), 395603. https://doi.org/10.1088/0957-4484/22/39/395603.

Lv, Y., Zhang, Z., Yan, J., Zhao, W. and Zhai, C. (2018), "Al doping influences on fabricating ZnO nanowire arrays: Enhanced field emission property", *Ceram. Int.*, **44**(7), 7454-7460. https://doi.org/10.1016/j.ceramint.2018.01.118.

Manzano, C.V., Alegre, D., Caballero-Calero, O., Alén, B. and Martín-González, M.S. (2011), "Synthesis and luminescence properties of electrodeposited ZnO films", *J. Appl. Phys.*, **110**(4), 043538. https://doi.org/10.1063/1.3622627.

Mittal, M., Sharma, M. and Pandey, O.P. (2014), "UV-Visible light induced photocatalytic studies of Cu doped ZnO nanoparticles prepared by co-precipitation method", *Solar Energy*, **110**, 386-397. https://doi.org/10.1016/j.solener.2014.09.026.

Monshi, A., Foroughi, M.R. and Monshi, M.R. (2012), "Modified Scherrer equation to estimate more accurately nano-crystallite size using XRD", *World J. Nano Sci. Eng.*, **2**(3), 154-160. https://doi.org/10.4236/wjnse.2012.23020.

Moussa, H., Girot, E., Mozet, K., Alem, H., Medjahdi, G. and Schneider, R. (2016), "ZnO rods/reduced graphene oxide composites prepared via a solvothermal reaction for efficient sunlight-driven photocatalysis", *Appl. Catal. B Environ.*, **185**, 11-21. https://doi.org/10.1016/j.apcatb.2015.12.007.

Naveed Ul Haq, A., Nadhman, A., Ullah, I., Mustafa, G., Yasinzai, M. and Khan, I. (2017), "Synthesis approaches of zinc oxide nanoparticles: the dilemma of ecotoxicity", *J. Nanomater.*, 2017. https://doi.org/10.1155/2017/8510342.

Noah, N.M. (2020), "Design and synthesis of nanostructured materials for sensor applications", *J. Nanomater.*, 2020. https://doi.org/10.1155/2020/8855321.

Ong, C.B., Ng, L.Y. and Mohammad, A.W. (2018), "A review of ZnO nanoparticles as solar photocatalysts: Synthesis, mechanisms and applications", *Renew. Sust. Energ. Rev.*, **81**, 536-551. https://doi.org/10.1016/j.rser.2017.08.020.

Panda, D. and Tseng, T.Y. (2013), "One-dimensional ZnO nanostructures: Fabrication, optoelectronic properties and device applications", *J. Mater. Sci.*, **48**(20), 6849-6877. https://doi.org/10.1007/s10853-013-7541-0.

Pant, H.R., Pant, B., Sharma, R.K., Amarjargal, A., Kim, H.J., Park, C.H., Tijing, L.D. and Kim, C.S. (2013), "Antibacterial and photocatalytic properties of $Ag/TiO_2/ZnO$ nano-flowers prepared by facile one-pot hydrothermal process", *Ceram. Int.*, **39**(2), 1503-1510. https://doi.org/10.1016/j.ceramint.2012.07.097.

Pimentel, A., Samouco, A., Nunes, D., Araújo, A., Martins, R. and Fortunato, E. (2017), "Ultra-fast microwave synthesis of ZnO nanorods on cellulose substrates for UV sensor applications", *Materials*, **10**(11), 1308. https://doi.org/10.3390/ma10111308.

Pirhashemi, M., Habibi-Yangjeh, A. and Rahim Pouran, S. (2018), "Review on the criteria anticipated for the fabrication of highly efficient ZnO-based visible-light-driven photocatalysts", *J. Ind. Eng. Chem.*, **62**, 1-25. https://doi.org/10.1016/j.jiec.2018.01.012.

Poongodi, G., Anandan, P., Kumar, R.M. and Jayavel, R. (2015), "Studies on visible light photocatalytic and antibacterial activities of nanostructured cobalt doped ZnO thin films prepared by sol-gel spin coating method", *Spectrochim. Acta A*, **148**, 237-243. https://doi.org/10.1016/j.saa.2015.03.134.

Poornaprakash, B., Chalapathi, U., Babu, S. and Park, S.H. (2017), "Structural, morphological, optical and magnetic properties of Gd-doped and (Gd, Mn) co-doped ZnO nanoparticles", *Physica E*, **93**, 111-115. https://doi.org/10.1016/j.physe.2017.06.007.

Pung, S.Y., Lee, W.P. and Aziz, A. (2012), "Kinetic study of organic dye degradation using ZnO particles with different morphologies as a photocatalyst", *Int. J. Inorg. Chem.*, 2012. https://doi.org/10.1155/2012/608183.

Qi, K., Cheng, B., Yu, J. and Ho, W. (2017), "Review on the improvement of the photocatalytic and antibacterial activities of ZnO", *J. Alloy Compd.*, https://doi.org/10.1016/j.jallcom.2017.08.142.

Rai, R.C. (2013), "Analysis of the Urbach tails in absorption spectra of undoped ZnO thin films", *J. Appl. Phys.*, **113**(15), 153508. https://doi.org/10.1063/1.4801900.

Rai, R.S. and Bajpai, V. (2019), "Fabrication of ZnO nanostructures on woven carbon fiber via hydrothermal route and effect of synthesis conditions on morphology", *International Conference on Precision, Meso, Micro and Nano Engineering*, 1-4.

Rai, R.S. and Bajpai, V. (2020), "Hydrothermally grown ZnO NSs on Bi-Directional woven carbon fiber and effect of synthesis parameters on morphology", *Ceram. Int.*, **47**(6), 8208-8217. https://doi.org/10.1016/j.ceramint.2020.11.180.

Ramimoghadam, D., Bin Hussein, M.Z. and Taufiq-Yap, Y.H. (2013), "Hydrothermal synthesis of zinc oxide nanoparticles using rice as soft biotemplate", *Chem. Central J.*, **7**(1), 1-10. https://doi.org/10.1186/1752-153X-7-136.

Rangel-Mendez, J.R., Matos, J., Cházaro-Ruiz, L.F., González-Castillo, A.C. and Barrios-Yáñez, G. (2018), "Microwave-assisted synthesis of C-doped TiO2and ZnO hybrid nanostructured materials as quantum-dots sensitized solar cells", *Appl. Surf. Sci.*, **434**, 744-755. https://doi.org/10.1016/j.apsusc.2017.10.236.

Ren, Q., Cao, Y.-Q., Arulraj, D., Liu, C., Wu, D., Li, W.-M. and Li, A.-D. (2020), "Resistive-type hydrogen sensors based on zinc oxide nanostructures", *J. Electrochem. Soc.*, **167**(6), 067528. https://doi.org/10.1149/1945-7111/ab7e23.

Sabry, R.S. and AbdulAzeez, O. (2013), "Hydrothermal growth of ZnO nano rods without catalysts in a single step", *Manuf. Lett.*, **2**(1), 69-73. https://doi.org/10.1016/j.mfglet.2014.02.001.

Salahuddin, N.A., El-kemary, M. and Ibrahim, E.M. (2015), "Synthesis and characterization of ZnO nanotubes by hydrothermal method", *Int. J. Sci. Res. Publ.*, **5**(9), 3-6.

Samadi, M., Zirak, M., Naseri, A., Khorashadizade, E. and Moshfegh, A.Z. (2016), "Recent progress on doped ZnO nanostructures for visible-light photocatalysis", *Thin Solid Films*, **605**, 2-19. https://doi.org/10.1016/j.tsf.2015.12.064.

Samuel, E., Joshi, B., Kim, M.W., Kim, Y. Il, Swihart, M.T. and Yoon, S.S. (2019), "Hierarchical zeolitic imidazolate framework-derived manganese-doped zinc oxide decorated carbon nanofiber electrodes for high performance flexible supercapacitors", *Chem. Eng. J.*, **371**, 657-665. https://doi.org/10.1016/j.cej.2019.04.065.

Sánchez Zeferino, R., Barboza Flores, M. and Pal, U. (2011), "Photoluminescence and raman scattering in ag-doped zno nanoparticles", *J. Appl. Phys.*, **109**(1), 014308. https://doi.org/10.1063/1.3530631.

Sathya, M. and Pushpanathan, K. (2017), "Synthesis and optical properties of Pb doped ZnO nanoparticles", *Appl. Surf. Sci.*, **449**, 346-357. https://doi.org/10.1016/j.apsusc.2017.11.127.

Sayari, A. and El Mir, L. (2015), "Structural and optical characterization of Ni and Al co-doped ZnO nanopowders synthesized via the sol-gel process", *KONA Powder Particle J.*, **32**(32), 154-162. https://doi.org/10.14356/kona.2015003.

Schmidt, R., Gonjal, J.P. and Morán, E. (2015), "Microwaves: Microwave assisted hydrothermal synthesis of nanoparticles", *Concise Encyclopedia Nanotechnol.*, **12**, 561-572.

Shetti, N.P., Bukkitgar, S.D., Reddy, K.R., Reddy, C.V. and Aminabhavi, T.M. (2019), "ZnO-based nanostructured electrodes for electrochemical sensors and biosensors in biomedical applications", *Biosens. Bioelectron.*, **141**, 111417. https://doi.org/10.1016/j.bios.2019.111417.

Shirvanimoghaddam, K., Hamim, S.U., Karbalaei Akbari, M., Fakhrhoseini, S.M., Khayyam, H., Pakseresht, A.H., Ghasali, E., Zabet, M., Munir, K.S., Jia, S., Davim, J.P. and Naebe, M. (2017), "Carbon fiber reinforced metal matrix composites: Fabrication processes and properties", *Compos. Part A Appl. S.*, **92**, 70-96. https://doi.org/10.1016/j.compositesa.2016.10.032.

Sin, J.C. and Lam, S.M. (2016), "Hydrothermal synthesis of europium-doped flower-like ZnO hierarchical structures with enhanced sunlight photocatalytic degradation of phenol", *Mater. Lett.*, **182**, 223-226. https://doi.org/10.1016/j.matlet.2016.06.126.

Sirelkhatim, A., Mahmud, S., Seeni, A., Kaus, N.H.M., Ann, L.C., Bakhori, S.K.M., Hasan, H. and Mohamad, D. (2015), "Review on zinc oxide nanoparticles: Antibacterial activity and toxicity mechanism", *Nano. Lett.*, **7**(3), 219-242. https://doi.org/10.1007/s40820-015-0040-x.

Sun, C., Shi, J. and Wang, X. (2010), "Fundamental study of mechanical energy harvesting using piezoelectric nanostructures", *J. Appl. Phys.*, **108**(3), 034309.https://doi.org/10.1063/1.3462468.

Sun, L., Shao, R., Chen, Z., Tang, L., Dai, Y. and Ding, J. (2012), "Alkali-dependent synthesis of flower-like ZnO structures with enhanced photocatalytic activity via a facile hydrothermal method", *Appl. Surf. Sci.*, **258**(14), 5455-5461. https://doi.org/10.1016/j.apsusc.2012.02.034.

Sun, Y., Guo, H., Zhang, W., Zhou, T., Qiu, Y., Xu, K., Zhang, B. and Yang, H. (2016), "Synthesis and characterization of twinned flower-like ZnO structures grown by hydrothermal methods", *Ceram. Int.*, **42**(8), 9648-9652. https://doi.org/10.1016/j.ceramint.2016.03.051.

Hasanpoor, M., Aliofkhazraei, M. and Delavari, H (2015), "Microwave assisted synthesis of Zinc oxide nanoparticles", *Procedia Mater. Sci.*, **11**, 320-325. https://doi.org/10.1016/j.mspro.2015.11.101.

Theerthagiri, J., Salla, S., Senthil, R.A., Nithyadharseni, P., Madankumar, A., Arunachalam, P., Maiyalagan, T. and Kim, H.S. (2019), "A review on ZnO nanostructured materials: Energy, environmental and biological applications", *Nanotechnology*, **30**(39), 392001. https://doi.org/10.1088/1361-6528/ab268a.

Tokumoto, M.S., Briois, V., Santilli, C.V. and Pulcinelli, S.H. (2003), "Preparation of ZnO nanoparticles: Structural study of the molecular precursor", *J. Sol Gel Sci. Technol.*, **26**(1), 547-551. https://doi.org/10.1023/A:1020711702332.

Kang, M. and Kim, H.S. (2016), "Microwave-assisted facile and ultrafast growth of ZnO nanostructures and proposition of alternative microwave-assisted methods to address growth stoppage", *Scientific Reports*, **6**(1), 1-13. https://doi.org/10.1038/srep24870.

Umar, A., Algarni, H., Kim, S. H. and Al-Assiri, M.S. (2016), "Time dependent growth of ZnO nanoflowers with enhanced field emission properties", *Ceram. Int.*, **42**(11), 13215-13222. https://doi.org/10.1016/j.ceramint.2016.05.114.

Velayutham, T.S., Abd Majid, W.H., Gan, W.C., Khorsand Zak, A. and Gan, S.N. (2012), "Theoretical and experimental approach on dielectric properties of ZnO nanoparticles and polyurethane/ZnO nanocomposites", *J. Appl. Phys.*, **112**(5), 054106. https://doi.org/10.1063/1.4749414.

Venkatesha, T.G., Arthoba Nayaka, Y., Viswanatha, R., Vidyasagar, C.C. and Chethana, B.K. (2012), "Electrochemical synthesis and photocatalytic behavior of flower shaped ZnO microstructures", *Powder Technol*., **225**, 232-238. https://doi.org/10.1016/j.powtec.2012.04.021.

Wang, F., Qin, X., Guo, Z., Meng, Y., Yang, L. and Ming, Y. (2013), "Hydrothermal synthesis of dumbbell-shaped ZnO microstructures", *Ceram*. *Int*., **39**(8), 8969-8973. https://doi.org/10.1016/j.ceramint.2013.04.096.

Wang, M., Ren, F., Zhou, J., Cai, G., Cai, L., Hu, Y., Wang, D., Liu, Y., Guo, L. and Shen, S. (2015), "N doping to ZnO nanorods for photoelectrochemical water splitting under visible light: engineered impurity distribution and terraced band structure", *Scientific Reports*, **5**(1), 1-13. https://doi.org/10.1038/srep12925.

Wang, R. Z., Zhao, W. and Yan, H. (2017), "Generalized mechanism of field emission from nanostructured semiconductor film cathodes", *Scientific Reports*, **7**(1), 1-8. https://doi.org/10.1038/srep43625.

Wang, S., Kuang, P., Cheng, B., Yu, J. and Jiang, C. (2018), "ZnO hierarchical microsphere for enhanced photocatalytic activity", *J*. *Alloy Compd*., **741**, 622-632.https://doi.org/10.1016/j.jallcom.2018.01.141.

Wang, X., Ahmad, M. and Sun, H. (2017), "Three-dimensional ZnO hierarchical nanostructures: Solution phase synthesis and applications", *Materials*, **10**(11), 1-24. https://doi.org/10.3390/ma10111304.

Wang, Y., Feng, J., Wang, H., Zhang, M., Yang, X., Yuan, R. and Chai, Y. (2020), "Fabricating porous ZnO/Co_3O_4 microspheres coated with N-doped carbon by a simple method as high capacity anode", *J*. *Electroanal*. *Chem*., **873**, 114479. https://doi.org/10.1016/j.jelechem.2020.114479.

Wang, Z.L. (2004), "Zinc oxide nanostructures: Growth, properties and applications", *J*. *Phys*. *Condens*. *Mat*., **16**(25), https://doi.org/10.1088/0953-8984/16/25/R01.

Wei, Y., Wang, X., Yi, G., Zhou, L., Cao, J., Sun, G., Chen, Z., Bala, H. and Zhang, Z. (2017), "Hydrothermal synthesis of Ag modified ZnO nanorods and their enhanced ethanol-sensing properties", *Mater*. *Sci*. *Semiconduct*. *Proc*., **75**, 327-333. https://doi.org/10.1016/j.mssp.2017.11.007.

Weldegebrieal, G.K. (2020), "Synthesis method, antibacterial and photocatalytic activity of ZnO nanoparticles for azo dyes in wastewater treatment: A review", *Inorg*. *Chem*. *Commun*., 108140. https://doi.org/10.1016/j.inoche.2020.108140.

Witkowski, B.S., Dluzewski, P., Kaszewski, J., Wachnicki, L., Gieraltowska, S., Kurowska, B. and Godlewski, M. (2018), "Ultra-fast epitaxial growth of ZnO nano/microrods on a GaN substrate, using the microwave-assisted hydrothermal method", *Mater*. *Chem*. *Phys*., **205**, 16-22. https://doi.org/10.1016/j.matchemphys.2017.11.005.

Wu, Y., Hermkens, P.M., Van De Loo, B.W.H., Knoops, H.C.M., Potts, S.E., Verheijen, M.A., Roozeboom, F. and Kessels, W.M.M. (2013), "Electrical transport and Al doping efficiency in nanoscale ZnO films prepared by atomic layer deposition", *J*. *Appl*. *Phys*., **114**(2), 024308. https://doi.org/10.1063/1.4813136.

Xiao, L., Li, E., Yi, J., Meng, W., Wang, S., Deng, B. and Liu, J. (2018), "Enhancing the performance of nanostructured ZnO as an anode material for lithium-ion batteries by polydopamine-derived carbon coating and confined crystallization", *J*. *Alloy Compd*., **764**, 545-554. https://doi.org/10.1016/j.jallcom.2018.06.081.

Xu, C.L. and Wang, Y.Z. (2018), "Self-assembly of stearic acid into nano flowers induces the tunable surface wettability of polyimide film", *Mater*. *Des*., ***138***, 30-38. https://doi.org/10.1016/j.matdes.2017.10.057.

Xu, S. and Wang, Z.L. (2011), "One-dimensional ZnO nanostructures: Solution growth and functional properties", *Nano Res*, **4**(11), 1013-1098. https://doi.org/10.1007/s12274-011-0160-7.

Yilmaz, M. (2015), "Investigation of characteristics of ZnO:Ga nanocrystalline thin films with varying dopant content", *Mater*. *Sci*. *Semiconduct*. *Proc*., **40**, 99-106. https://doi.org/10.1016/j.mssp.2015.06.031.

Yilmaz, M., Bozkurt Cirak, B., Cirak, C. and Aydogan, S. (2016), "Hydrothermal growth of ZnO nanoparticles under different conditions", *Phil*. *Mag*. *Lett*., **96**(2), 45-51. https://doi.org/10.1080/09500839.2016.1144938.

Yoo, R., Yoo, S., Lee, D., Kim, J., Cho, S. and Lee, W. (2017), "Highly selective detection of dimethyl methylphosphonate (DMMP) using CuO nanoparticles /ZnO flowers heterojunction", *Sensor Actuat*. *B Chem*., **240**, 1099-1105. https://doi.org/10.1016/j.snb.2016.09.028.

Yu, W., Zhang, J. and Peng, T. (2016), "New insight into the enhanced photocatalytic activity of N-, C- and S-doped ZnO photocatalysts", *Appl*. *Catal*. *B Environ*., **181**, 220-227. https://doi.org/10.1016/j.apcatb.2015.07.031.

Yuan, G., Xiang, J., Jin, H., Wu, L., Jin, Y. and Zhao, Y. (2018), "Anchoring ZnO nanoparticles in nitrogen-doped graphene sheets as a high-performance anode material for lithium-ion batteries", *Materials*, **11**(1), 96. https://doi.org/10.3390/ma11010096.

Yun, H., Zhou, X., Zhu, H. and Zhang, M. (2021), "One-dimensional zinc-manganate oxide hollow nanostructures with enhanced supercapacitor performance", *J*. *Colloid Interf*. *Sci*., **585**, 138-147. https://doi.org/10.1016/j.jcis.2020.11.060.

Yusof, N.A.A., Zain, N.M. and Pauzi, N. (2019), "Synthesis of ZnO nanoparticles with chitosan as stabilizing agent and their antibacterial properties against Gram-positive and Gram-negative bacteria", *Int*. *J*. *Biol*. *Macromol*., **124**, 1132-1136. https://doi.org/10.1016/j.ijbiomac.2018.11.228.

Zhao, X., Li, M. and Lou, X. (2014), "Sol-gel assisted hydrothermal synthesis of ZnO microstructures: Morphology control and photocatalytic activity", *Adv*. *Powder Technol*., **25**(1), 372-378. https://doi.org/10.1016/j.apt.2013.06.004.

Zheng, N., Huang, Y., Sun, W., Du, X., Liu, H.Y., Moody, S., Gao, J. and Mai, Y.W. (2016), "In-situ pull-off of ZnO nanowire from carbon fiber and improvement of interlaminar toughness of hierarchical ZnO nanowire/carbon fiber hydrid composite laminates", *Carbon*, **110**, 69-78. https://doi.org/10.1016/j.carbon.2016.09.002.

Zhu, P., Yin, X., Gao, X., Dong, G., Xu, J. and Wang, C. (2020), "Enhanced photocatalytic NO removal and toxic NO2 production inhibition over ZIF-8-derived ZnO nanoparticles with controllable amount of oxygen vacancies", *Chinese J*. *Catal*., **42**(1), 175-183. https://doi.org/10.1016/S1872-2067(20)63592-6.

Zhu, Z., Yang, D. and Liu, H. (2011), "Microwave-assisted hydrothermal synthesis of ZnO rod-assembled microspheres and their photocatalytic performances", *Adv*. *Powder Technol*., **22**(4), 493-497. https://doi.org/10.1016/j.apt.2010.07.002.

Znaidi, L. (2010), "Sol-gel-deposited ZnO thin films: A review", *Mater*. *Sci*. *Eng*. *B*, **174**(1-3), 18-30. https://doi.org/10.1016/j.mseb.2010.07.001.

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