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Doped ZnO Nanostructured and their application as photocatalytic: as Review

Abstract

There are two types of methods of synthesis of several different kinds of doped ZnO nanomaterials for photocatalytic applications, gas phase methods, include pulsed laser deposition and chemical vapor deposition and wet chemical methods such as sol–gel, electrospinning, hydrothermal, spray pyrolysis, thermo-mechanical .doping with metal ions is make local energies levels within the semiconductor energy gap, which results in prolongation of the light absorbance to the visible light region. Several studies have that metal-doped ZnO, such as N, S, and C, using Co, Fe, Cu, Eu, Ce, Ag, Mn, and Al and non-metal doping, ZnO to the reducing Energies and enhancement of photocatalytic behavior in the region of visible light.

Introduction

Nonmetals and metals were analyzed in order to transform ZnO's electronic structure to expose a shift in absorption, metals were assessed. Various properties, including Crystal design, pore size, surface area, and doped ZnO photocatalytic activity, depending on the dopant shape, concentrations, and conditions of preparation. Therefore, separate metal doping, non-metal doping becomes less likely to create recombination centers, doping generates a novel state of the valence band that leads to a reduction of the band gap by high upward valence band limit . [1-3] Amornpitoksuk et al. [4] formulated Nano-crystalline Ag-doped ZnO powders with different concentrations of Ag precursors through a minimal temperature precipitation process. They find that Ag ions add ZnO lattice by replacement on Zn^{2+} sites when Ag loading is less than 0.5 mol%

Ga and Ag doped ZnO Nano rods, supported in polyethylene by a hydrothermal microwave heating synthesis and evaluated their photocatalytic performance and antimicrobial activity towards two bacterial strains commonly found on treated-water effluents. [5]Fe-doped zinc oxide Nano star was synthesized by the process of microwave-assisted surfactant-free hydrolysis Various synthetic protocols for the synthesis of various ZnO nanostructures and literature including direct calcination of metal salt have been widely published [6], sol-gel method [7] and hydrothermal synthesis [8], simply hydrolysis followed by calcination [9-10]

Due to its equivalent physical and Chemical properties, an ideal doping for ZnO The optical properties of the micro structure [11-12] can be modified[13-15] band-gap decreases, absorption shifts to longer wavelengths (16) and ZnO nanostructure morphology changes

Polat et al[17] prepared Cu-doped ZnO Nano rods for methylene blue degradation On glass substrates by the deposition of chemical baths (CBD). A morphological change from pyramidal geometry to hexagonal rod shapes has been observed .Zhang et al. [18]has successfully doped Cr precursor into ZnO Nano rods by hydrothermal method, and Cr-doped ZnO cluster may be the most favorable sensor for CO detection because its electrical conductivity considerably changes after the CO adsorption. Cr-doped ZnO used in the gas sensing studies of reducing and toxic gas such as ammonia; and volatile .Cd doped ZnO resulted in reduction in bandgap [19] which cause to the tuning of luminescence to visible region. Cd-doped ZnO powders synthesized by kinds methods including sono chemical method [20], hydrothermal method [21-22], sol–gel synthesis [23], and chemical synthesis method [24]. As compared to the corresponding pure oxides, the Co_3O_4/ZnO catalysts showed modified textural characteristics. The demonstrated catalytic behaviors were substantially greater than those of the pure oxides. Catalyst Co_3O_4/ ZnO .The most active is formulated with zinc carbonate (CoZnOTC) by thermal decomposition, while the least active is the catalyst synthesized with citric acid as fuel (CoZnOSCI) by sol gel combustion.[25].In order to prepare Co doped ZnO thin film including spray pyrolysis, the sol-gel method[26] has

unique advantages such as low cost, easy deposition process, fast adjustment of composition as well as the manufacture of wide area films and dopants [27], magnetron sputtering [28] pulsed laser deposition[PLD] [29], Several studies have centered on magnetic Co/ ZnO' and electrical properties. [30-31], Without any major distortion in the lattic e structure, Co(II) can be substituted for Zn(II)sites since the Co(II) ionic radiu s is smaller than the Zn(II) [32-34]. Moshfegh's group have successfully modified ZnO nanoparticles through band gap engineering to visible-light-active photo catalysts [35-42].In oxidation discolorations of contaminant fabric coloring dye reactive black in slurry reactor, that metal(Mn, Ni, Co, Ag, and Cu)-doped activated ZnO powders have higher photocatalytic activities compared to that of pure ZnO outstanding in its photocatalytic efficiency. the state of being discolored of the dye result to afflicted charge carrier separation and the rise specific surface area .Unmodified ZnO has been shown a four times lower degradation rate than silver modified ZnO and a Three times less rate than the commercial TiO2 photocatalyst (Georgekutty et al. 2008)[43] .pure zinc oxide displayed in reaction for methyl red degradation in solutions, a similar behavior compared to Ag-N-co-doped ZnO nanoparticles under UV irradiation (Welderfael. 2013). (Kant 2012) [44] indicates that the Ni dopant has an important impact under the UV-visible region on photocatalytic activity .Ag\Fe_2O_3-doped ZnO nanostructures were fabricated for photo oxidation of methyl blue (MB) dye under visible light irradiation. The photocatalytic activity of ZnO and Ag-ZnO nanostructure which studied in presence visible light, using Cibacron Brilliant Yellow 3G-P CB dye

The photocatalytic activity of the Ag doped ZnO nanofibers were determined the degradation of methylene blue(MB) under UV light irradiation. It was found that higher (MB) degradation rate resulted ability of fibers was improved with Ag addition and higher Ag incorporation. For pure ZnO fibers, the degradation of its initial amount was 52% of methylene blue after 270 min of UV irradiation time. Fe has oxidation states to increase the activity of ZnO photo catalysts applied to Fe. ZnO doping with Fe and Cr will lead to the production of a ferromagnetic character photo catalyst that promotes environmental congregation after photo oxidation. property important of Fe dopant is a number of states of oxidation, namely Fe^{4+}, Fe^{3+} ,and Fe^{2+} [45-48]

$ZnO + hv \rightarrow e^- + h^+$ (1)

$Fe^{3+} + e_{CB-} \rightarrow Fe^{2+}$ (electron trap) (2)

$Fe^{2+} + O_{2(ads)} \rightarrow F^{3+} + O_2^-$ (3)

$Fe^{3+} + h_{VB}^+ \rightarrow Fe^{4+}$ (hole trap) (4)

$Fe^{4+} + OH^- \rightarrow Fe^{3+} + \cdot OH$(hole release) (5)

To degrade the contaminants, the active oxidant species are OH· and O2-· radicals. The supply of Fe-induced traps increases if Fe is doped in concentrations greater than the optimum concentration. the production of Fe^{3+} and Fe^{2+}, Fe sites work as recombination centers because Fe4+ interacts with electrons and Fe2+ interacts with a hole to provide Fe3+ . therefore the photo-induced electron/hole will not, photocatalytic activity reduces and produce active oxidant species.The nanostructures of Mn doped ZnO have higher rate constant and photo degradation efficiency as it has higher surface defects, crystallinities and length, than others. Some researchers have reported that the opposite results while the Mn doped ZnO increases the photocatalytic activity under UV irradiation [49-50].Tsuzuki et al.

evaluated the Mn-doped ZnO nanoparticles and undoped that doping with Mn reduced the photocatalytic activity of ZnO for the degradation of RhB dye . Compared to undoped ZnO, Cu/ ZnO doping has been found to result in increased photocatalytic activity (Fu et al. 2011) [51]. Liu et al. (2008) [52] and Xu et al. (2010) [53] stated that the photocatalytic efficiency was enhanced by the implementation of Cu2O and CuO.. Ekambaram et al. (2007) [54] stated that Mn/ZnO, Co/ZnO, and ZnO less active than Ni-doped ZnO. Influence of Co-/Mn-/ Cu-doping on the photocatalytic performance of the ZnO nanostructures. Lead to effects of types in morphology, surface defects, that porosity and high specific surface areas played a significant role in modulating the photocatalytic activity of ZnO nanostructures. For the photocatalytic degradation of methyl orange by Cu-doped ZnO nanoparticles under UV light. Results indicate that higher Cu concentrations decrease the recombination rate of photo-generated electrons and holes. Fu et al. [55] Mohan et al. [56] by prepared Nano rods For the photo-degradation of resazurin dye, using the vapor transport process. Cu/ Zince Oxide Nano rods with narrower band gap. The band differences in ZnO and CuO are 3.4 eV and 1.2 eV [57-60]. They may be used in the photo decomposition of various materials under UV irradiation in aqueous media [61-63].by preparing CZO-rGO nanocomposite by reduced graphene oxide (r GO) Nano sheets to extend the light adsorption and to improve the efficiency of the separation of photo generated electron-hole pair and the light harvesting [64-72].

using a facile hydrothermal method synthesized Cd doped ZnO nanostructures. The sunlight induced photocatalytic activity was evaluated towards the degradation of methylene blue (MB)dye.an increase in Cd dopant concentration in ZnO showed a redshift in The UV–Visible absorption spectra. The spectra show defect-related visible emission band and near band edge emission . Cd/ZnO exhibits photo degradation of (MB)dye compared to undoped ZnO , because Cd^{2+} ion capture photogenerated electrons and restrain recombination of electron and hole [73-75].During the preparation process, the addition of Co ion into ZnO nanoparticles results in small particle size with a large surface area preferred for photocatalytic. [76-78]. And also connected to the combined effects of higher defect concentration and vacancies in oxygen [79-80].Several studies shown that Co doped ZnO increases the activity nanomaterials of ZnO; in some reports, it significantly decreases [81-86] .The higher rate of increase porosity in the glassy process after silica consumption. Because the presence of (ZrO2) results to the formation of (ZrSiO4) . The addition of ZrO2 to DD3 clay in a previous work gives the highest amount of porosity on the ceramic surface [87]. Transition metal oxides are some of the catalysts used in current photo degradation. ZnO is among the oxides that Changes in the morphology of Nanoparticale zinc oxide [88-89] photocatalytic activity for Al-doped ZnO was investigated [90]. More studies show that the process variables synthesis technique affects the properties of Al-doped zinc oxide and the formation of a broader [91-92] or smaller Al-doped ZnO band gap [93-94].Due to the collapse of small pores in the ZnO sample during calcination, N-doped ZnO has a smaller specific surface area than pure ZnO using NH4NO3 as the nitrogen source obtained by Wu [95], When preparing N/ZnO for

visible-light photo degradation by sol-gel process and the source of nitrogen using urea of picloram herbicides and 2,4-D by Macias. [96]. different amounts of nitrogen doping were obtained band gap and crystallite size for various different surface areas. Their results show provides the highest photocatalytic efficiency , The band gap is decreased by 0.19 eV . Nanocomposites were Synthesized of N/ ZnO/g-C3N4 core shell Nano plates for rhodamine B by visible-light oxidation process and the comparison to g-C3N4 and pure ZnO [97] .Cho et al. [98] formulated vitamin C with a carbon dopant source for C-doped ZnO Nanomaterials and studied the effect of visible light on orange-II dye by photo degradation. In order to elucidate the formulation of C_O and Zn C bonds, they have used (EDS), XRD, and XPS representation. [99-100].photocatalytic activity and stability are increasing using Cerium/ ZnO nanomaterials [101-102]. Ionic radii of Zn^{2+} ion is much smaller than both Ce^{4+} and Ce^{3+}.Ce doping causes surface area increase ,crystallite and particle size decrease, Favored for the reactions of photo-catalysis [103].Zinc oxide Valence band with different energy levels, induced by new electronic transition states and visible-light absorption obtains [104].In addition, The red shift and blue shift occur through doping at the optical absorption edge of ZnO. Showing a rise in dopant concentrations of Eu. Furthermore, the highest photo degradation occurs in 0.2 % Eu-doped ZnO. [105] of methyl orange .Zeng et al. [106] prepared Eu-doped ZnO nanoparticles with a wider band gap compared to pure ZnO, which contributes to enhanced photocatalytic activity under UV light. Their PL emission spectra indicate a slower e/h recombination rate Anandan et al. [107] synthesized La-doped ZnO nanomaterials for degradation of 2,4,6-trichlorophenol by precipitation method. by increasing in La dopant concentration results to band gap broadening and crystal size decrease Because of the formation of the La O Zn bond on the surface that hinders crystal grain growth. Therefore, smaller particle size and appropriate active sites for pollutant adsorption are given by greater surface area.Khataee et al[108] by the Sono Chemical Method prepared Dy-doped ZnO nanoparticles for acid red 17 degradation. Under visible-light irradiation, Dy/ ZnO shows the strongest photocatalytic decolorization. The stronger photocatalytic operation for the association between two Dy^{3+} and Dy^{4+} oxidation states is Dy-doped ZnO .using for visible-light-active photo catalysts with other elements by co-doping of Al-doped ZnO (AZO) nanocrystals [109], for photocatalytic hydrogen production by Huo et al. [110] synthesized Y doped AZO by the sol-gel process. Their results show that pure ZnO smaller optical absorption in the whole light region than the Y-AZO nanoparticles. The major effects of the co-doping process on the catalytic efficiency of doped ZnO within the visible range are shown in the figure. 1.

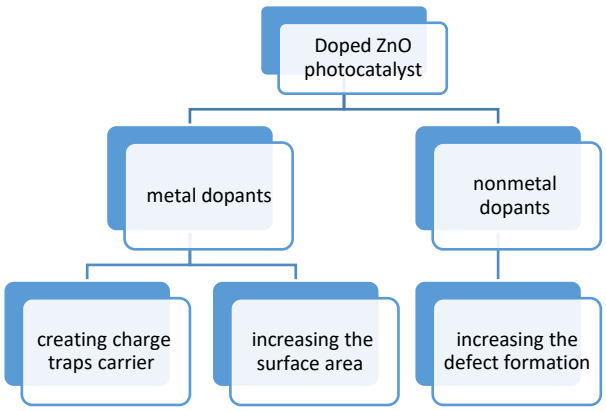

Fig. (1). General features of nonmetal and metal doping of ZnO photo catalyst under the visible-light.

An appealing configuration is also explored to change the electronic structure and extend the absorption of visible light by integrating rare-earth (RE) atoms in the ZnO structure. The energy gap shifts are due to I) formulation of local defect level band by RE metals ii) the ionized impurities using potential variation introduced, iii) ZnO conduction or valence band variance and 4f ,5d states of RE metals by charge transport [111].In addition, doping results in the efficient suppression of the recombination of the photo-generated (hole/electron). This results in the RE metal's ability to trick the electrons ,For several applications, photo catalysis is applied in more fields, like water and air control [112], disinfection processes [113], self-cleaning methods [114], renewable energy sources, such as the production of hydrogen by water splitting [115], green chemical synthesis [116] and CO2 reduction for hydrocarbons [116] [117]. ZnO photo catalysts' industrial uses in electric fields are showing in figure 2 .

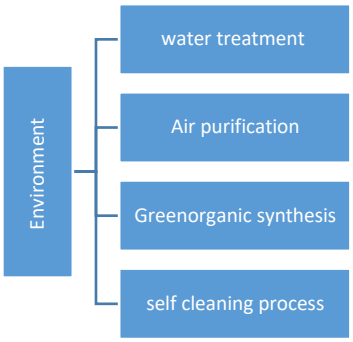

Fig. (2) Photocatalytic environment applications of Zinc oxide

A donor state, obtained by replacing atoms with one or more electrons in the outer shell with n-type ZnO doping compared to the substitution atom (Zn or O) in ZnO. As a result, Replacement of group-VII elements at O sites and group-III elements at Zn sites by highly conductive n-type ZnO-type elements. Substitution of group-V on O sites and group-I elements on Zn sites, of p-type ZnO doping, provides an acceptor stage. While ZnO can easily be doped with the n-type, efforts to produce reliable p-type doping are yet a problem due to higher ionization, p-type dopant low solubility. [118-120].

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Reference

[1] Yuyraj S., Malghe B. , Lavand (Synthesis, characterization and visible light photocatalytic activity of carbon and iron modified ZnO) Journal of King Saud University - Science , Volume 30, Issue 1(2018)pp. 65-7

[2]J. Li, N. Wu (Semiconductor-based photo catalysts and photo electrochemical cells for solar fuel generation: a review) Catal. Sci. Technol., 5 (2015), pp. 1360-1384
Cross Ref Scopus Google

[3] Chen X, Shen S, Guo L, Mao S.S. (Semiconductor-based photocatalytic hydrogengeneration)Chem.
Rev. 110 (2010), pp. 6503-6570
Cross Ref View Record in Scopus Google Scholar[4] Amornpitoksuk . S, Suwanboon, A. Sangkanu, . Sukhoom, J.Muensit, Baltrusaitis (Synthesis, characterization, photocatalytic and antibacterial activities of Ag-doped ZnO powders modified with a diblock copolymer) Powder Technol., 219 (2012), pp. 158-164

[5] Marlene N. , Contreras C., Gallegos A, Limon A, José M , Herrera R, Águila S, Contreras O. E. (Photocatalytic and Antimicrobial Properties of Ga Doped and Ag Doped ZnO Nano rods for Water Treatment) Catalysts , 9(2019)165

[6] Zhang K.-Z, Lin B.-Z, Chen Y.-L. (Fe-doped and ZnO pilla redtitanates as visible-light-driven photo catalysts,) Journal of Colloid and Interface Science, vol. 358, no. 2(2011)pp. 360–368,.

[7] Hernandez A, Maya L, S ´anchez-Mora E, S´ anchez E. M ,(Sol-gel synthesis, characterization and photocatalytic activity of mixed oxide ZnO-Fe2O3) Journal of Sol-Gel Science and Technology, vol. 42, no. 1(2007) pp. 71–78.

[8] Han L, Wang D, Lu Y. (Influence of annealing temperature on the photoelectric gas sensing of Fe-doped ZnO under visible light irradiation) Sensors and Actuators B: Chemical, vol.177(2013) pp. 34–40.

[9] Dong S, Xu K, Liu J, Cui H. (Photocatalytic performance of ZnO :Fe array films under sunlight irradiation) Physica B:Condensed Matter, vol. 406, no. 19, (2011)pp. 3609–3612.

[10] Lung Kwong T, Yung K Fu (Surfactant-Free Microwave-Assisted Synthesis of Fe-Doped ZnO Nano stars as Photo catalyst for Degradation of Tropaeol in O in Water under Visible Light)Journal of Nanomaterials Volume 2015, Article ID 190747,(2015) pp.9

[11] Bahsi Z.B, Oral A.Y. (Effects of Mn and Cu doping on the microstructures and optical properties of sol–gel derived ZnO thin films) Opt. Mater. 29 (2007) 672-678.

[12] Kumar R, Umar A, Kumar G, Akhtar M.S, Wang Y, Kim M.S. (Ce-doped ZnO nanoparticles for efficient photocatalytic degradation of direct red-23 dye) Ceram. Int. 41(6), (2015) 7773-7782.

[13] Ashokkumar M, Muthukumaran S,(Effect of Ni doping on electrical, photoluminescence and magnetic behavior of Cu doped ZnO nanoparticles) J. of Luminescence 162 (2015) 97–103.

[14] Herng T, Lau S, Yu S, Yang H, Wang L, Tanemura M. (Magnetic anisotropy in the ferromagnetic Cu-doped ZnO Nano-needles) Appl. Phys. Lett. 90 (2007) 032509.

[15] Baicker M, Wang D, Wang J, Li Q, Sun J, Yan Y. (Cu-doped ZnO nanorod arrays: the effects of copper precursor and concentration) Nanoscale Res. Lett. 9 (2014) 1-9.

[16] Robak1E, Coy E, Kotkowiak M, Jurga S, Załęski1K, Drozdowski H, (The effect of Cu doping on the mechanical and optical properties of zinc oxide nanowires synthesized by hydrothermal route) Nanotechnology, 27 (2016) 175706

[17] Polat P ,Jongnavakit, P. Amornpitoksuk, Suwanboon S, Ndiege N (Preparation and photocatalytic activity of Cu-doped ZnO thin films prepared by the sol–gel method)Appl. Surf. Sci., 258 (2012), pp. 8192-8198

[18] Zhang G , H. (Morphology controlled syntheses of Cr doped ZnO single-crystal nanorods for acetone gas sensor) Mater. Lett.165(2016) 83–86.

[19] Phuruangrat A, Mad-ahin S, Yayapao O, Thongtem S, ThongtemT. (Photocatalytic degradation of organic dyes by UV light, catalyzed by nanostructured Cd-doped ZnO synthesized by a sonochemical method) Res. Chem. Intermediates. 41 (2015) , 9757-9772

[20] Kaushal A, Pathak D, Bedi R, Kaur D. (Structural, electrical and optical properties of transparent Zn1− xMgxO nanocomposite thin films) Thin Solid Films 518,(2009) 1394-1398.

[21] Khayat S, Abaker M, Umar A, Alkattan M, Alharbi N, Basoutas S. (Synthesis and Characterizations of Cd-Doped ZnO Multifoods for Environmental Remediation Application) J. Nano sci. Nano technol. vol. 12,No.11 (2012) 8453-8468

[22] Hong D, Cao G, Zhang X, Qu J, Deng Y, Liang H, Tang J .(Construction of a Pt-modified chestnut-shell-like ZnO photo catalyst for high-efficiency photochemical water splitting) Electro chimica Acta. 283, (2018) 959-969

[23] Khoddadi B, Bordbar M, Yeganeh A.F (Optical, structural, and photocatalytic properties of Cd-doped ZnO powders prepared via sol–gel method) J. Sol–Gel. Sci. Technol.77 (2016) 521-527

[24] Jagtap C, Kadam V, Ghogare T, Inamdar Y, Shaikh A, Mane R, Shaikh A(Pristine and cadmium-doped zinc oxide: chemical synthesis and characterizations) J. Mater. Sci.: Mater. Electron. 27 (2016) 12335-–12339

[25] Sahar A. El-Molla, Ali L. I, Mahmoud H. R , Ibrahim M. M, Naghmash A. M. (Effect of preparation method, loading of Co3O4 and calcination temperature on the physicochemical and catalytic properties of Co_3O_4/ZnO nanomaterials)Materials Chemistry and Physics (2016) 1-11.

[26] Caglar Y. (Sol–gel derived nanostructure undoped and cobalt doped ZnO: Structural, optical and electrical studies)J. Alloys Compd. 560 (2013) pp. 181-188

[27] Vijayalakshmi S , Venkataraj S, Subramanian M, Jayavel R. ("Physical properties of zinc doped tin oxide films prepared by spray pyrolysis technique)J. Phys. D Appl. Phys., 41 (035505) (2008), pp. 1-7

[28] Kao C.Y, Liao J.D , Chan C. W. Wang R.Y. (Thermal diffusion of Co into sputtered ZnO: Co thin film for enhancing visible-light-induced photo-catalytic activity, Applied Surface Science)Appl. Surf. Sci., 258 (2011), pp. 1813-1818

[29] Zhang Y , Guo T, Luo Y.D, Lin Y.H, Nan C.W. (Tunable Ferromagnetic Behaviors Observed in Highly Orientated Co-Doped ZnO Thin Films by the Bandgap

Engineering)J. Am. Ceram. Soc., 96 (2) (2013), pp. 361-364

[30] Yildiz A, Yurduguzel B, Kayhan B, Calin G, Dobromir, Iacomi F. (Electrical conduction properties of Co-doped ZnO nanocrystalline thin films)J. Mater. Sci. Mater. Electron, 23 (2012), pp. 425-430

[31] Li J, Zhang L, J. Zhu, Liu Y, Hao W, Li B. (Controllable synthesis and magnetic investigation of ZnO: Co nanowires and nanotubes) Mater. Lett., 87 (2012), pp. 101-104

[32] Thennarasu G, Sivasamy A. (Metal ion doped semiconductor metal oxide Nano sphere particles prepared by soft chemical method and its visible light photocatalytic activity in degradation of phenol)Powder Technol., 250 (2013), pp. 1-12

[33] Rajbongshi B.M, Samdarshi S.K. (ZnO and Co-ZnO nanorods — complementary role of oxygen vacancy in photocatalytic activity of under UV and visible radiation flux)Mater. Sci. Eng., B, 182 (2014), pp. 21-28

[34] Lima M.K, Fernandes D.M, Silva M.F, Baesso M.L, Neto A.M, Morais G.R. Nakamura C.V, De Oliveira A. leare, A. Hechenleitner A.W. , Pineda E.A.G. (Co-doped ZnO nanoparticles synthesized by an adapted sol–gel method: Effects on the structural, optical, photocatalytic and antibacterial properties)J. Sol-Gel Sci]
. Technol., 72 (2014), pp. 301-309

[35] Samadi M, Shivaee H.A, Zanetti M, Pourjavadi A, Moshfegh A.Z. (Visible light photocatalytic activity of novel MWCNT-doped ZnO electro spun nanofibers)
J. Mol. Catal. A Chem., 359 (2012), pp. 42-48

[36]Pelaez, Nolan N.T, Pillai S.C, Seery M.K, Falaras P, Kontos A.G, Dunlop P.S.M, Hamilton J.W.J, Byrne J.A, O'Shea K, Entezari M.H, Dionysiou D.D. (A review on the visible light active titanium dioxide photo catalysts for environmental applications)Appl. Catal. B Environ., 125 (2012), pp. 331-349

[37] Naseri N, Yousefi M, Moshfegh A.Z (A comparative study on photo electrochemical activity of ZnO/TiO_2 and TiO_2/ZnO Nano layer systems under visible irradiation) Sol. Energy, 85 (2011), pp. 1972-1978

[38] Yousefi M, Amiri M, Azimirad R, Moshfegh A.Z. (Enhanced photo electrochemical activity of Ce doped ZnO nanocomposite thin films under visible light)J. Electro anal. Chem., 661 (2011), pp. 106-112

[39] Samadi M, Shivaee H.A, Pourjavadi A. , Moshfegh A.Z. (Synergism of oxygen vacancy and carbonaceous species on enhanced photocatalytic activity of electro spun ZnO-carbon nanofibers: charge-carrier scavengers mechanism)
Appl. Catal. A Gen., 466 (2013), pp. 153-160

[40] Zirak M, Moradlou O, Bayati M, Nien Y, Moshfegh A.Z. (On the growth and photocatalytic activity of the vertically aligned ZnO nanorods grafted by CdS shells) Appl. Surf. Sci., 273 (2013), pp. 391-398

[41] Zirak M, Akhavan O, Moradlou O, Nien Y, Moshfegh A.Z. (Vertically aligned ZnO@ CdS Nano rod hetero structures for visible light photo inactivation of bacteria)J. Alloys Compd., 590 (2014), pp. 507-513

[42] Samadi M, Pourjavadi A, Moshfegh A.Z. (Role of CdO addition on the growth and photocatalytic activity of electro spun ZnO nanofibers: UV vs. visible light)
Appl. Surf. Sci., 298 (2014), pp. 147-154

[43] Georgekutty R, Seery MK , Pillai SC . (A highly efficient Ag-ZnO photo catalyst: synthesis, properties, and mechanism) J Phys ChemC112,35, (2008):13563–13570. doi:10.1021/jp802729a

[44] Kant S, Kumar A . (A comparative analysis of structural, optical and photo catalytic properties of ZnO and Ni doped ZnO Nano spheres prepared by sol gel method) Adv Mat Let 3,4, (2012):350–354. doi:10.5185/amlett.2012.5344

[45] Yi S, Cui J, Li S, Zhang L, Wang D, Lin Y. (Enhanced visible-light photocatalytic activity of Fe/ZnO for rhodamine B degradation and its photogenerated charge transfer properties)Appl. Surf. Sci., 319 (2014), pp. 230-236

[46] Chakma S, Moholkar V.S. (Investigation in mechanistic issues of sono catalysis and sono photo catalysis using pure and doped photo catalysts)Ultra son. Sono chem., 22 (2015), pp. 287-299]

[47] Saleh R, Djaja N.F. (UV light photocatalytic degradation of organic dyes with Fe-doped ZnO nanoparticles)Superlattice.
Microst., 74 (2014), pp. 217-233

[48] Kumar K, Chitkara M, Sandhu I.S, Mehta D, Kumar S. (Photocatalytic, optical and magnetic properties of Fe-doped ZnO nanoparticles prepared by chemical route)J. Alloys Compd., 588 (2014), pp. 681-689

[49] Dodd A, McKinley A, Tsuzuki T, Saunders M (Tailoring the photocatalytic activity of Nano particulate zinc oxide by transition metal oxide doping)
Materials chemistry and physics, 114 (2009) 382-386.

[50] Fan L, Wang J, Qiu N, Liu Y, . Zhang X (Photocatalytic Activities of Vertically Aligned Manganese-Doped ZnO Nano rods Synthesized on ITO Film by lectro chemical Technique) Int. J. Electro chem. Sci. 2019 ,Vol. 14.

[51] Fu M, Li Y, Wu S , Lu P , Liu J, Dong F. (Sol–gel preparation and enhanced photocatalytic performance of Cu-doped ZnO nanoparticles)Appl Surf Sci 258(2011)1587–1591

[52] Liu Z-L , Deng J-C, Deng J-J, Li F-F . (Fabrication and photo catalysis
of CuO/ZnO Nano-composites via a new method) Mater Sci Eng B150(2008) 99–104. doi:10.1016/j.mseb.2008.04.002

[53] Xu C , Cao L , Su G , Liu W, Liu H, Yu Y , Qu X . (Preparation of ZnO/Cu2Ocompound photo catalyst and application in treating organic dyes)
J Hazard Mater 176(2010) 807–813. doi:10.1016/j.jhazmat.2009.11.106

[54] Ekambaram S, Iikubo Y , Kudo A . (Combustion synthesis and photocatalytic properties of transition metal-incorporated ZnO) JAlloy Comp 433(2007) 237–240. doi:10.1016/j.jallcom.2006.06.045

[55] Fu M, Li Y, Wu S, Lu P, Li ,J, Dong F. (Sol–gel preparation and enhanced photocatalytic performance of Cu-doped ZnO nanoparticles)
Appl. Surf. Sci., 258 (2011), pp. 1587-1591

[56] Mohan R, Krishnamoorthy K, Kim S.J. (Enhanced photocatalytic activity of

Cu-doped ZnO Nano rods)Solid State Common., 152 (2012), pp. 375-380
[57] Huang J, Dai Y, Gu C, Sun Y, Liu J. (Preparation of porous flower-like CuO/ZnO nanostructures and analysis of their gas-sensing property) J. Alloys Comp. 575 (2013) 115–122.
[58] Zaman S. (Synthesis of ZnO, CuO and their Composite Nanostructures for Optoelectronics, Sensing and Catalytic Applications) thesis Linköping University, Sweden,(2012).
[59] Sharma R. K, Ghose R. (Synthesis of monocrystalline CuO–ZnO mixed metal oxide powder by a homogeneous precipitation method) Ceram. Int. 40 (2014) 10919–10926.
[60] Pukird S, Song W, Noothongkaew S, Kim S. K, Min B. K, Kim S. J, Kim K. W, Myung S, An K. S. (Synthesis and electrical characterization of vertically-aligned ZnO –CuO hybrid nanowire p – n junctions) Appl. Surf. Sci. 351 (2015)546–549.
[61] Marto J, São Marcos P, Trindade T, Labrincha J.A. (Photocatalytic discoloration of Orange II by ZnO active layers screen-printed on ceramic tiles) J. Hazard. Mater. 163 (2009) 36–42.
[62] Rego E, Marto J, Marcos P. S, Labrincha J.A. (Discoloration of Orange II solutions by TiO2 and ZnO active layers screen-printed on ceramic tiles under sunlight irradiation) Appl. Catal. A: Gen. 355(2009)109–114.
[63] Kanade K. G, Kale B. B, Baeg J. O, Lee S. M, Lee C. W, Moon S. J, Chang H. (Self assembled aligned Cu doped ZnO nanoparticles for photocatalytic hydrogen production under visible light irradiation) J. Mater. Chem. Phys. 102 (2007) 98 – 104.
[64] Forgacs E, Cserháti T, Oros G. (Removal of synthetic dyes from wastewaters: a review, Environment International) 30 (2004) 953-971.
[65] Özgür Ü, Alivov Y.I, Liu C, Teke A, Reshchikov M.A, Doğan S, Avrutin V, Cho S.J, Morkoç H. (A comprehensive review of ZnO materials and devices) Journal of Applied Physics, 98 (2005) 041301.
[66] Banerjee D, Lao J.Y, Wang D.Z, Huang J.Y, Steeves D, Kimball B, Ren Z.F. (Synthesis and photoluminescence studies on ZnO nanowires) Nanotechnology, 15 (2004) 404.
[67] Schulz D, Ganschow S, Klimm D, Struve K. (Inductively heated Bridgman method for the growth of zinc oxide single crystals) Journal of Crystal Growth, 310 (2008) 1832-1835.
[68] Sunandan B, Chanchana T, Joydeep D. (Growth of ZnO nanowires on nonwoven polyethylene fibers) Science and Technology of Advanced Materials, 9 (2008) 025009.
[69] Sunandan B, Joydeep D. (Hydrothermal growth of ZnO nanostructures) Science and Technology of Advanced Materials, 10 (2009) 013001.
[70] Takahashi K, Yoshikawa A, Sandhu A. (Wide bandgap semiconductors) Springer-Verlag Berlin Heidelberg., (2007) 239.
[71] Kumar S.S, Venkateswarlu P, Rao V.R, Rao G.N. (Synthesis, characterization and optical properties of zinc oxide nanoparticles)International Nano Letters, 3 (2013) 30.
[72] Spaniel L, Anderson M.A. (Semiconductor clusters in the sol-gel process: quantized aggregation, gelation, and crystal growth in concentrated zinc oxide colloids)Journal of the American Chemical Society, 113 (1991) 2826-2833.
[73] Wang Y, Thomas P, Brien P. (Optical Properties of ZnO Nanocrystals Doped with Cd, Mg, Mn, and Fe Ions) J. Phys. Chem. 10, 43(2006)21412–21415
[74] Zhou S Meng X, Zhang X, Fan X, Zou K, Wu S, Lee S. (Large-scale fabrication

and characterization of Cd-doped ZnO nanocantilever arrays)
Micron 36, 55 (2005)
[75] Yakuphanoglu F, Ilican S, Caglar M, Caglar Y. (Microstructure and electro-optical properties of sol–gel derived Cd-doped ZnO films) Super lattices Micro structure. 47, 732 (2010)
[76] Kuriakose S, Satpati B, Mohapatra S. (Enhanced photocatalytic activity of Co doped ZnO nanodisks and Nano rods prepared by a facile wet chemical method)
Phys. Chem. Chem. Phys., 16 (2014), pp. 12741-12749

[٧٧] Thennarasu G, Sivasamy A. (Metal ion doped semiconductor metal oxide Nano sphere particles prepared by soft chemical method and its visible light photocatalytic activity in degradation of phenol)Powder Technol., 250 (2013), pp. 1-12
[78] Xu C, Cao L, Su G, Liu W, Qu X, Yu Y. (Preparation, characterization and photocatalytic activity of Co-doped ZnO powders)
J. Alloys Compd., 497 (2010), pp. 373-376

[79] Rajbangsi B.M, Samdarshi S.K. (ZnO and Co-ZnO Nano rods — complementary role of oxygen vacancy in photocatalytic activity of under UV and visible radiation flux Mater. Sci. Eng., B, 182 (2014), pp. 21-28
[80] Xiao Q, Zhang J, Xiao C, Tan X. (Photocatalytic decolonization of methylene blue over $Zn_{1-x}Co_xO$ under visible light irradiation) Mater. Sci. Eng., B, 142 (2007), pp. 121-125

[81] Barick K.C, Singh S, Aslam M, Bahadur D. (Porosity and photocatalytic studies of transition metal doped ZnO nanoclusters)Microporous Mesoporous Mater., 134 (2010), pp. 195-202

[82] Dodd A, McKinley A, Tsuzuki T, Saunders M. (Tailoring the photocatalytic activity of Nano particulate zinc oxide by transition metal oxide doping)Mater. Chem. Phys., 114 (2009), pp. 382-386

[83] Kaur J, Singhal S. (Facile synthesis of ZnO and transition metal doped ZnO nanoparticles for the photocatalytic degradation of methyl orange)Ceram. Int., 40 (2014), pp. 7417-7424
[84] Lima M.K, Fernandes D.M , Silva M.F, Baesso M.L, Neto A.M, G.R. Morais, Nakamura C.V, de Oliveira A. l, Hechenleitner A.A.W, Pineda E.A.G. (Co-doped ZnO nanoparticles synthesized by an adapted sol–gel method: Effects on the structural, optical, photocatalytic and antibacterial properties)J. Sol-Gel Sci. Technol., 72 (2014), pp. 301-309

[85] He R , Hocking R.K, Tsuzuki T. (Local structure and photocatalytic property of sol–gel synthesized ZnO doped with transition metal oxides)J. Mater. Sci., 47 (2012), pp. 3150-3158

[86] He R, Hocking R.K, Tsuzuki T. (Co-doped ZnO nanopowders: location of cobalt and reduction in photocatalytic activity)Mater. Chem. Phys., 132 (2012), pp. 1035-1040
[87] Mecif A, Soro J, Harabi A, Bonnet J. P. (Preparation of Mullite- and Zircon-Based Ceramics Using Kaolinite and Zirconium Oxide: A Sintering Study) J. Am. Ceram. Soc, 93(5) (2010) 1306 –1312.
[88] Herng T, Lau S, Yu S, Yang H, Wang L, Tanemura M (Magnetic anisotropy in the ferromagnetic Cu-doped ZnO Nano-

needles)Appl. Phys. Lett. 90 (2007) 032509.
[89] Babikier M, Wang D, Wang J, Li Q, Sun J, Yan Y, (Cu-doped ZnO nanorod arrays: the effects of copper precursor and concentration) Nanoscale Res. Lett. 9 (2014)1-9.
[90] Pal M, Bera S, Sarkar S, Jana S. (Influence of Al doping on microstructural, optical and photocatalytic properties of sol–gel based nanostructured zinc oxide films on glass) RSC Adv., 4 (2014), pp. 11552-11563

[91] Ramírez D, Álvarez K, Riveros G, Tejos M, Lobos M.G. (New insights on the doping of ZnO films with elements from group IIIA through electrochemical deposition)J. Solid State Electrochemist., 18 (2014), pp. 2869-2884

[92] Bizarro M, Sánchez-A A, Garduño-W I , Alonso J.C, Ortiz A. (Synthesis and characterization of ZnO and ZnO: Al by spray pyrolysis with high photocatalytic properties) Catal. Today, 166 (2011), pp. 129-134

[93] Ahmad M, Ahmed E, Zhang Y, Khalid N.R, Xu J, Ullah M, Hong Z. (Preparation of highly efficient Al-doped ZnO photo catalyst by combustion synthesis)Current. Appl. Phys., 13 (2013), pp. 697-704

[94] Shahjahan M, Khan M.K.R, Hossain M.F, Biswas S, Takahashi T. (Structural, optical, and photocatalytic properties of ZnO: Al nanoball structure deposited on glass substrate by spray pyrolysis) J. Vac. Sci. Technol. A, 27 (2009), pp. 885-888

[95] Wu C. (Facile one-step synthesis of N-doped ZnO micro polyhedrons for efficient photocatalytic degradation of formaldehyde under visible-light irradiation)Appl. Surf. Sci., 319 (2014), pp. 237-243

[96] Macías-S J.J, Hinojosa-R L, Caballero-Q A, Cruz W. De La, Ruiz E, Hernández A, Guzmán-M J.L. (Synthesis of nitrogen-doped ZnO by sol–gel method: characterization and its application on visible photocatalytic degradation of 2,4-D and pictograms herbicides)Photochemical. Photobiology. Sci., 14 (2015), pp. 536-542

[97] Kumar S, Baruah A, Tonda S, Kumar B, Shanker V, Sreedhar B. (Cost-effective and eco-friendly synthesis of novel and stable N-doped ZnO/g-C_3N_4 core-shell nameplates with excellent visible-light responsive photo catalysis)Nanoscale, 6 (2014), pp. 4830-4842

[98] Cho S, Jang J.W, Lee J.S, Lee K.H. (Carbon-doped ZnO nanostructures synthesized using vitamin C for visible light photo catalysis) Cryst. Eng. Comm, 12 (2010), pp. 3929-3935
[99] Zhu Y.P, Li M, Liu Y.L, Ren T.Z, Yuan Z.Y. (Carbon-doped ZnO hybridized homogeneously with graphitic carbon nitride nanocomposites for photo catalysis)
J. Phys. Chem. C, 118 (2014), pp. 10963-10971
[100] Li J, Zhao K, Yu Y, Zhang L. (Facet-level mechanistic insights into general homogeneous carbon doping for enhanced solar-to-hydrogen conversion)Adv. Funct. Mater., 25 (2015), pp. 2189-2201
[101] Rezaei M, Habibi-Yangjeh A. (Simple and large scale refluxing method for preparation of Ce-

doped ZnO nanostructures as highly efficient photocatalyst)
Appl. Surf. Sci., 265 (2013), pp. 591-596

[102] Kannadasan N, Shanmugam N, Cholan S, Sathishkumar K, Viruthagiri G, Poonguzhal R. (iThe effect of Ce^{4+} incorporation on structural, morphological and photocatalytic characters of ZnO nanoparticles)Mater. Charact., 97 (2014), pp. 37-46

[103] Rezaei M, Habibi- Yangjeh A. (Microwave-assisted preparation of Ce-doped ZnO nanostructures as an efficient photo catalyst)Mater. Lett., 110 (2013), pp. 53-56

[104] Anandan S, Miyauchi M. Ce-doped ZnO ($Ce_xZn_{1-x}O$) becomes an efficient visible-light-sensitive photocatalyst by co-catalyst (Cu^{2+}) grafting)Phys. Chem. Chem. Phys., 13 (2011), pp. 14937-14945

[105] Sin J.C, Lam S.M, Satoshi I, Lee K.T, Mohamed A.R. (Sunlight photocatalytic activity enhancement and mechanism of novel europium-doped ZnO hierarchical micro/Nano spheres for degradation of phenol)Appl. Catal. B Environ., 148-149 (2014), pp. 258-268

[106] Zong Y, Z. Li, Wang X, Ma J, Men Y. (Synthesis and high photocatalytic activity of Eu-doped ZnO nanoparticles)Ceram. Int., 40 (2014), pp. 10375-10382

[107] Anandan S, Vinu A, Mori T, Gokulakrishnan N, Srinivasu P, V. Murugesan, Ariga K. (Photocatalytic degradation of 2,4,6-trichlorophenol using lanthanum doped ZnO in aqueous suspension)(Catal. Common., 8 (2007), pp. 1377-1382

[108] Khataee A , Soltani R.D.C. , Hanifehpour Y. , Safarpour M , Gholipour H. Ranjbar, . Joo S.W (Synthesis and characterization of dysprosium-doped ZnO nanoparticles for photo catalysis of a textile dye under visible light irradiation)Ind. Eng. Chem. Res., 53 (2014), pp. 1924-1932

[109] Wang J.D , Liu J.K , Tong Q. , Lu Y , Yang X.H. (High degradation activity and quantity production of aluminum-doped zinc oxide nanocrystals modified by nitrogen atoms)Ind. Eng. Chem. Res., 53 (2014), pp. 2229-2237

[110] Huo J , Fang L. , Lei Y. , Zeng G, Zeng H. (Facile preparation of yttrium and aluminum co-doped ZnO via a sol–gel route for photocatalytic hydrogen production)
J. Mater. Chem. A, 2 (2014), pp. 11040-11044

[111] Iqbal J , Liu X , Zhu H , Wu Z.B , Zhang Y. , D. Yu, R. Yu(Raman and highly ultraviolet red-shifted near band-edge properties of LaCe-co-doped ZnO nanoparticles)Acta Mater., 57 (2009), pp. 4790-4796

[112] Kumar S.G. , Rao K.S.R.K. (Zinc oxide based photo catalysis: tailoring surface-bulk structure and related interfacial charge-carrier dynamics for better environmental applications)RSC Adv., 5 (2015), pp. 3306-3351

[113] Guo Z , Chen X , Li J , Liu J. H , Huang X. J. (ZnO/CuO hetero-hierarchical Nano trees array: hydrothermal preparation and self-cleaning properties)
Langmuir, 27 (2011), pp. 6193-6200

[114] Fujishima A , Honda K. (Electrochemical photolysis of water at a semiconductor electrode)Nature (1972), pp. 37-38

[115] Lang X , Chen X , Zhao J (Heterogeneous visible light photo catalysis for selective organic

transformations)Chem. Soc. Rev., 43 (2014), pp. 473-486
[116] Seven O , Dindar B , Aydemir S , Metin D , Ozinel M , Icli S. (Solar photocatalytic disinfection of a group of bacteria and fungi aqueous suspensions with TiO_2, ZnO and Sahara desert dust)J. Photochemical. Photobiology. A Chem., 165 (2004), pp. 103-107
[117] Kudo A , Miseki Y. (Heterogeneous photo catalyst materials for water splitting)Chem. Soc. Rev., 38 (2009), pp. 253-278
[118] Pearton S.J , Norton D.P, Ip K. , Heo Y.W , Steiner T. (Recent progress in processing and properties of ZnO)Prog. Mater. Sci., 50 (2005), pp. 293-340
[119] Li J , Ma S. , Liu X , Zhou Z , Sun C.Q. (ZnO mesa –mechanic -thermos physical chemistry)Chem. Rev., 112 (2012), pp. 2833-2852
[120] KlingshirnC, Fallert J. Zhou, H, Sartor J, Thiele C, Maier-Flaig F, Schneider D, Kalt H. (65 years of ZnO research — old and very recent results)Phys. Status Solidi B, 247 (2010), pp. 1424-1447