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ORIGINAL ARTICLE

Synthesis and characterization of ZnO nanoparticles by thermal decomposition of a curcumin zinc complex

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Abstract ZnO nanoparticles were generated by thermal decomposition of a binuclear zinc (II) curcumin complex as single source precursor. Thermal behavior of the precursor showed a considerable weight loss at about 374 °C by an exothermic reaction with a maximum weight loss rate of 14%/min. Complete decomposition of precursor was observed within 49 min with a heating rate of 10 °C/min. Synthesized nanoparticles have been characterized by X-ray diffraction, Fourier transform infrared spectroscopy, transmission electron microscopy and selected area electron diffraction microscopy. Results revealed monodispersed hexagonal zincite structure with an average size of 117 ± 4 nm.

1. Introduction

Metal oxides are particularly attractive with respect to applications in catalysis, sensing, energy storage, conversion optics, electronic devices (Purica et al., 2001; Aoki et al., 2000), memory arrays, biomedical application (Ayudhya et al., 2006; Wu et al., 2006) and acoustic wave devices (Gorla et al., 1999). Zinc oxide nanocrystals are one of the most intensively studied materials because of their versatile optoelectronic applications. Their large band gap of 3.37 eV and large excitation binding energy of 60 meV ensure an efficient UV-blue emission at room temperature (Joo et al., 2005; Vafaee and Ghamsari, 2007; Kim et al., 2005). Because of this, ZnO has a great potential in several applications such as room temperature UV-lasers (Huang et al., 2001, Arnold et al., 2003, light emitting diodes (Park et al., 2002; Jo et al., 2003), solar cells (Rensmo et al., 1997) and sensors (Kind et al., 2002; Senoussaoui et al., 2004).

Various synthetic methods have been developed to fabricate ZnO nanocrystals including vapor phase growth (Sun et al., 2004), vapor liquid–solid processes (Gao and Wang, 2004), soft chemical method (Vayssieres, 2003), electrophoretic deposition (Liu et al., 2003), sol–gel processes (Zhang et al., 2003), solvothermal processes (Wang et al., 2006), and thermal decomposition techniques (Baskoutas et al., 2008; Niassari et al., 2005; Liewhiran et al., 2006; Xu et al., 2002). For example, ZnO nanocrystals with various shapes were synthesized

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using a variety of surfactants (Joo et al., 2005), by the thermal decomposition of zinc alginate at 800 and 450 °C (Baskoutas et al., 2008), or by using bis(acetylacetonate) zinc(II) as a precursor (Niassari et al., 2005). Nano-sized ZnO powders (10–60 nm) were synthesized by thermal decomposition of zinc acetate (Liewhiran et al., 2006). Using urea and zinc nitrate as raw materials, Liu et al., 2007, prepared zinc oxide nanocrystals by a homogeneous precipitation method followed by thermal treatment at 500 °C for 10 min. On the other hand, ketones have been used as an oxolation source for the synthesis of titanium-oxo-organo crystals (Steunou et al., 1999; Garnweitner et al., 2004). Analogously, the β-diketone curcumin and curcuminoids (1,7-diaryl-1,6-heptadiene-3,5 diones) which are a group of naturally occurring 1,3-diketones with a good ligating ability for metal ions (Tennesen and Greenhill, 1992; Krishnankutty and John, 2003) is an attractive area for exploring the potential of its metal complexes for the synthesis of metal oxides nanoparticles. Curcumin is a renewable resource, its metal complexes are easily prepared that can be used to prepare metal oxides nanoparticles with low cost. In the mean time, there is no published data over the synthesis of metal oxides nanoparticles using curcumin metal complexes as a single source precursor. In this study, we describe the synthesis of ZnO nanoparticles by the thermal decomposition of a binuclear zinc hydroxido curcumin complex as a precursor prepared by the reaction of $Zn(NO_3)_2{\cdot}6\,H_2O$ and curcumin in a 1:2 mol ratio (Khalil et al., 2013). The thermal behavior of the precursor metal complex was studied by thermogravimetric analysis (TGA), and differential thermal analysis (DTA). The synthesized ZnO nanocrystals were characterized by Fourier transform infrared (FTIR) spectroscopy, powder X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and selected area electron diffraction (SAED).

2. Experimental

2.1. Chemicals and materials

All the chemicals and solvents were of reagents grade and used without further purification as purchased from Sigma–Aldrich, New Jersey, USA. Zinc nitrate (BDH, Poole, England) laboratory reagent was used.

2.2. Analytical instruments

The FTIR spectrum was recorded on a Shimadzu FTIR-8400S, Prestige-21 spectrophotometer in a KBr matrix. TGA and DTA curves were recorded using a TA instrument model-SDT-Q600. XRD patterns were obtained by an Ultima IV X-ray diffractometer by using monochromatized Cu Kα 1 radiation under the acceleration voltage of 40 kV and a current of 40 mA. The morphology of the ZnO nanocrystals was examined by a JEOL JSM-6380 LA SEM and a JEOL TEM 2100F TEM with an acceleration voltage of 200 kV.

2.3. Preparation of zinc (II) curcumin complex

(Bis1,7-bis[4-hydroxy-3-methoxyphenyl]-1,6-heptadiene-3,5-dionato)hydroxide zinc(II), [Zn(OH)(curc)] was prepared by a previously reported method (Khalil et al., 2013). An ethanolic mixture solution of zinc nitrate and curcumin in a 1:2 mol ratio was refluxed for 1 h and the resulting product was filtered and washed several times by de-ionized water, dried in vacuum and used as a precursor to synthesize ZnO nanoparticles.

3. Results and discussion

3.1. Thermal decomposition of zinc (II) curcumin complex precursor

Our investigation revealed that such a complex lends itself as a potential precursor for zinc oxide nanoparticles synthesis through thermal decomposition. The thermal properties of precursor were determined by thermogravimetric analysis (TGA) and differential thermal analysis (DTA). Sample was heated in an aluminum pan from room temperature to 600 °C at a heating rate of 10 °C/min. The TGA and DTA analyses (Fig. 1) revealed that the complex looses 6% of its weight at about 200 °C attributed to desorption or removal of moisture and solvents, and 50% weight loss of its total

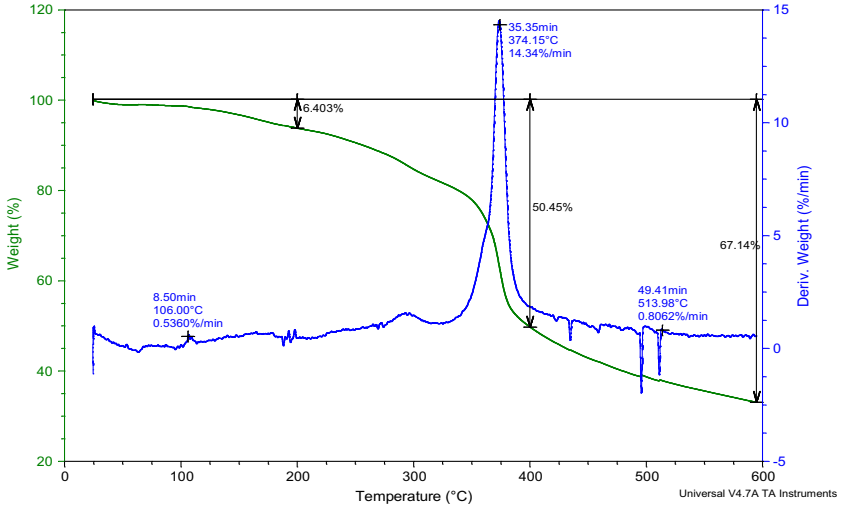

Figure 1 Thermal behavior of $[Zn\,(OH)C_{21}H_{20}O_6]_2$.

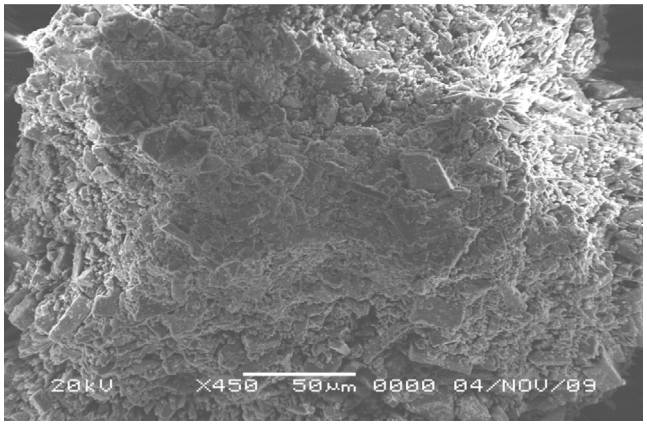

Figure 2 SEM image of $[Zn(OH)C_{21}H_{20}O_6]_2$ precursor.

weight at 374 °C with a maximum weight loss rate of 14% min^{-1} indicating a fast rate of degradation of curcumin into volatile combustible products. The DTA curve has a large exothermic peak at that temperature which may be attributed to the fact that volatile organic moieties generated by the dissociation of precursor react with O_2 to form CO_2 and H_2O. This is confirmed by the weight loss observed in the temperature region 400–600 °C in the TGA curve.

The morphology of the synthesized micro particles of the zinc complex precursor shown in the SEM image of Fig. 2 was converted into hexagonal nanoparticles upon thermal treatment at 500 °C.

The phase and crystallinity of the synthesized sample were investigated by X-ray diffraction patterns shown in Fig. 3. The patterns are in accord with the typical zincite structure ZnO diffraction (hexagonal phase, space group $P6_3mc$, with lattice constants $a = 3.24982$ Å, $c = 1.6021$ Å, $Z = 2$, JCPDS No. 361451) (Bigdeli et al., 2010; Liu et al., 2007).

A most intense peak at $2\theta = 36.67°$ is obtained along (1 0 1) orientation. The sharpness, strong intensity and narrow width of ZnO diffraction peaks in the XRD pattern indicate that the synthesized ZnO sample is well crystallized. The FTIR spectrum of ZnO nanoparticles exhibited two strong vibrational bands at 640 and 605 cm^{-1} assigned to the stretching modes

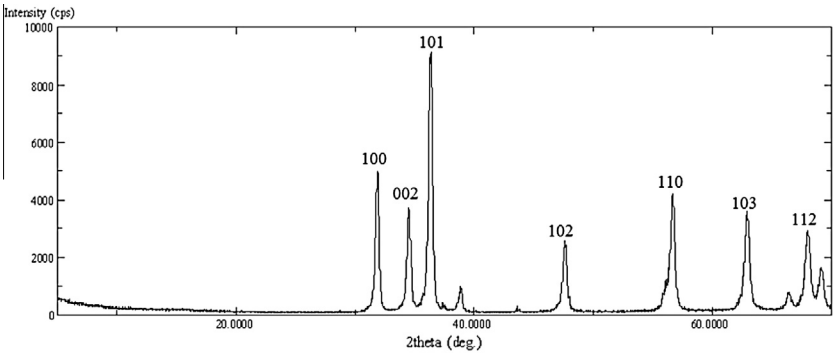

Figure 3 X-ray diffraction pattern of ZnO nanoparticles.

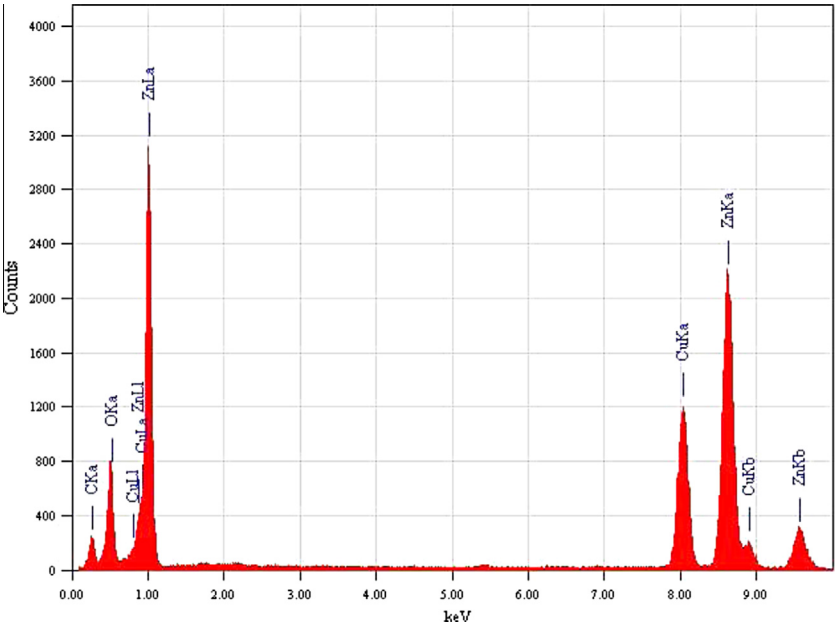

Figure 4 EDS pattern of the ZnO nanoparticle.

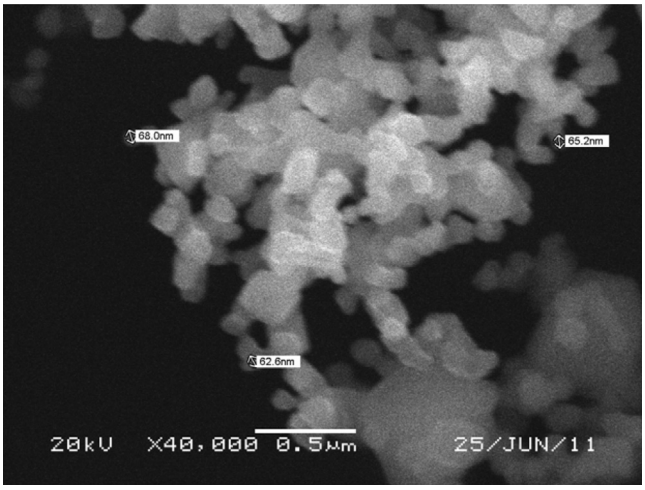

Figure 5 SEM image of ZnO nanoparticles.

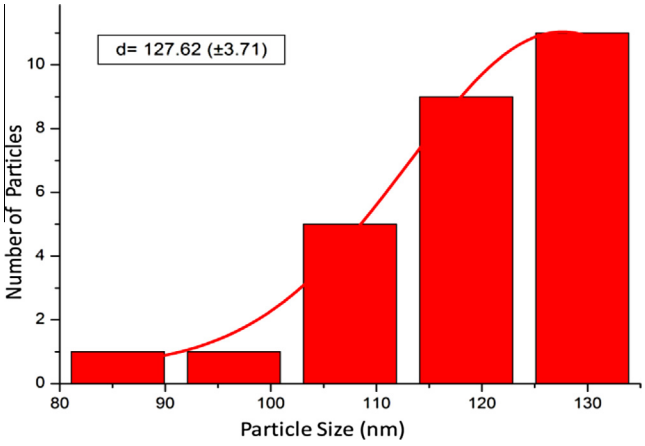

Figure 7 Histogram (average size) of ZnO nanoparticles.

of Zn–O and the weak bands at 3500 and 1040 cm^{-1} are probably attributed to the presence of water in the KBr matrix (Bigdeli et al., 2010; Chen et al., 2004). The EDS pattern of the ZnO nanoparticles is shown in Fig. 4. The Cu and C signals were from the Cu grid and carbon film coated on the support formvar. No other signals were detected within the detection limits of EDS which confirm the purity of the ZnO nanoparticles.

The scanning electron microscopy (SEM) image of ZnO sample is shown in Fig. 5. This image reveals that the ZnO is in nano scale.

The fine powder of ZnO nanocrystals was dispersed in ethanol on a carbon-coated copper grid and the high resolution transmission electron microscopy (HRTEM) images (Fig. 6) were obtained with ultra high resolution at an accelerating voltage of 200 kV. The selected area electron diffraction (SAED) pattern shown in insert (a) of Fig. 6 has sharp spots indicative of polycrystalline nature with symmetrical orientation of ZnO nanoparticles in the sample. The crystallinity of the synthesized nanoparticles was also supported by the observed lattice fringes of 0.25 nm in HRTEM image shown in insert (b) of Fig. 6. This value is very near the 0.26 ± 0.05 nm spacing for ZnO corresponding to (1 0 1) plane of ZnO (Yan et al., 2000).

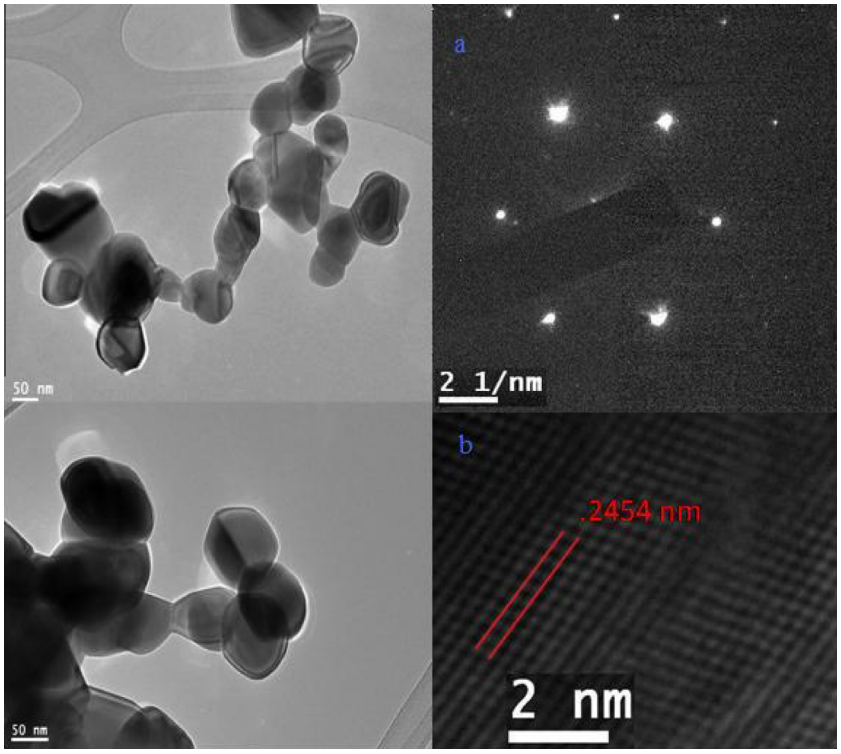

Figure 6 TEM image of ZnO nanoparticles, SAED (insert a) and high scanning resolution (insert b).

The average crystal size is estimated by considering the few number of crystals shown in the TEM image, Fig. 6, and found to be about 127 ± 4 nm presented by a histogram in Fig. 7.

4. Conclusion

The synthesis of zinc oxide nanoparticles from a curcumin zinc complex by a thermal decomposition technique was studied in this paper. Low heat energy was applied to degrade the organic moiety. Nanoparticles with an average size of 117 ± 4 nm were obtained from an easily prepared organic moiety containing metal complex precursor. Such a type of precursors have potential for synthesizing metal oxide nanoparticles.

Acknowledgement

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References

Aoki, T., Hatannaka, Y., Look, D.C., 2000. ZnO diode fabricated by excimer-laser dopping. Appl. Phys. Lett. 76, 3257. Aoki, et al., 2000. reported the fabrication of a ZnO diode by using a laser-doping technique. The surface changes and photoluminescence of three samples were measured. Poor electroluminescence was reported.

Arnold, M.S., Avouris, P., Pan, Z.W., Wang, Z.L., 2003. Field effect transistors based on single semiconducting oxide nanobelts. J. Phys. Chem. B 107 (3), 659. Arnold, et al., fabricated field-effect transistors based on single SnO_2 and ZnO nanobelts of thickness between 10 and 30 nm. Conductance and ultraviolet light sensitivity were reported. The results could be utilized in tuning the electrical performance of the electrical device.

Ayudhya, S.K.N., Tonto, P., Mekasuwandumrong, O., Pavarajarn, V., Praserthdam, P., 2006. Solvothermal synthesis of ZnO with various aspect ratios using organic solvents. Cryst. Growth Des. 6, 2446. Ayudhya, et al., synthesized nanocrystalline ZnO powders by a solvothermal method using various organic solvents as the reaction medium. Products were characterized by XRD, SEM, TEM, and SAED. The work opens a field of investigating the role of dielectric constant of solvents in nanomaterials synthesis.

Baskoutas, S., Gabournis, P., Yannopoulos, S.N., Dracopoulos, V., Toth, L., Chrissanthopoulos, A., Bouropoulos, N., 2008. Preparation of ZnO nanoparticles by thermal decomposition of zinc alginate. Mater. Lett. 62, 1890–1892, Baskoutas, et al., reported a method of ZnO nanocrystals production based on the thermal decomposition of zinc alginate gels.XRD, SEM and TEM analysis revealed the presence of ZnO hexagonal phase. The temperature and precursor used influenced the crystal size besides the existence of structural defects of nanoparticles.

Bigdeli, F., Morsali, A., Retalleau, P., 2010. Synthesis and characterization of different zinc (II) oxide nano-structures from direct thermal decomposition of ID coordination polymers. Polyhedron 29, 801–806, Bigdeli, et al., synthesized different ZnO nanostructures from direct thermal decomposition of ID co-ordination polymers. Their claims were documented by crystallographic measurements of precursors and TGA, IR, SEM, and EDAX measurements of ZnO particles. However, synthesis of precursors involved several chemicals and energy.

Chen, B.J., Sun, X.W., Xu, C.X., Tay, B.K., 2004. Growth and characterization of zinc oxide nano/micro-fibers by thermal chemical reactions and vapor transport deposition in air. Physica E 21, 103–107, Chen, et al., reported the preparation of ZnO nano/micro crystal fibers on silicon substrate via thermal chemical reactions vapor transport deposition method in air with a mixture of ZnO and carbon powders as reactants. Products were characterized by XRD and SEM techniques. However, very high temperature was used in the method.

Gao, P.X., Wang, Z.L., 2004. Nanopropeller arrays of zinc oxide. Appl. Phys. Lett. 84 (15), 2883, Gao and Wang, synthesized ZnO nanopropeller arrays by a two-step high temperature solid-vapor deposition process. They showed the modes of growth along the axes and a wide band gap. The study is of an applied physics nature.

Garnweitner, G., Antonietti, M., Niederberger, M., 2004. Nonaqueous synthesis of crystalline anatase nanoparticles in simple ketones and aldehydes as oxygen supplying agent. Chem. Commun., 397–399, Garnweitner, et al., obtained highly crystalline nanoparticles of 5–20 nm size by reacting titanium tetraisopropoxide with ketones and aldehydes as oxygen-supplying agents under solvothermal conditions. The XRD diffraction pattern and TEM image support their claims. The high concentration of the TiO_2 in the system and the potential for the synthesis of other binary and ternary metal oxides are promising aspects for practical applications.

Gorla, C.R., Emanetoglu, N.W., Liang, S., 1999. Structural, optical and surface aqoustic wave properties of epitaxial ZnO films grown on (011 over-bar2) sapphire by metalorganic chemical vapor deposition. J. Appl. Phys. 85 (5), 2595, Gorla, et al., reported growing high quality epitaxial ZnO films on R-plane sapphire substrates by metalorganic chemical vapor deposition. The properties of ZnO films were studied by TEM and photoluminescence techniques. The work is suitable for application in UV modulator.

Huang, M.H., Mao, S., Feick, H., Yan, H., Wu, Y., Kind, H., Webber, E., Russo, R., Yang, P., 2001. Room temperature ultraviolet nanowire nanolasers. Science 292, 1897, Huang, et al., demonstrated room-temperature ultraviolet lasing in semiconductor nanowire arrays. Oriented ZnO nanowires grown on sapphire substrates were synthesized with a vapor transport and condensation process. Band gaps and chemical flexibility were measured. Such nanolasers reported have promising applications.

Jo, S.H., Lao, J.Y., Ren, Z.F., Farrer, R.A., Baldacchini, T., Fourkas, J.T., 2003. Field-emission studies on thin films of zinc oxides nanowires. Appl. Phys. Lett. 83 (23), 4821, Jo et al., Studied the field emission(FE) from thin films of ZnO nanowires grown by the thermal evaporation/condensation method. The SEM images, X - ray diffraction patterns and FE current of samples were reported. The results of this work could be of importance in improving the FE current of ZnO nanowires.

Joo, J., Kwon, S.G., Yu, J.H., Hyeon, T., 2005. Synthesis of ZnO nanocrystals with cone, hexagonal cone, and rod shapes via non-hydrolytic ester elimination sol–gel reactions. Adv. Mater. 17, 1873–1877, Joo et al., reported the synthesis of ZnO nanocrystals with various shapes from the reaction of zinc acetate and 1,2-dodecane diol using a variety of surfactants. Their findings were well documented by SEM, TEM and HRTEM techniques. The work is leading in the field of ZnO nanoparticles synthesis.

Khalil, Mutasim I., Al zahem, Aisha M., Al-Qunaibit, Maha M., 2013. Synthesis, characterization and antitumor activity of binuclear curcumin-metal(II) hydroxo complexes. Med. Chem. Res. http://dx.doi.org/10.1007/s00044-013-0727-9.

Kim, Y.S., Tai, W.P., Shu, S.J., 2005. Effect of preheating temperature on structural and optical properties of ZnO thin films by sol–gel process. Thin Solid Films 4, 153, Kim, et al., reported the preparation of ZnO thin films on glass substrate by sol–gel spin-coating method. The transmittances of preheated ZnO films are reported to be 85% and the optical band gap energy is evaluated to be 3.24–3.26 eV. The discussion of the effect of preheating temperature on structural and optical properties is convincing.

Kind, H., Yan, H., Messer, B., Law, M., Yang, P., 2002. Nanowire ultraviolet photodetectors and optical switches. Adv. Mater. 14,

158, Kind et al., showed the possibility of creating highly sensitive nanowire switches by exploring the photoconducting properties of ZnO semiconductors nanowires grown by a vapor phase transport process with diameters ranging from 50 to 300 nm. Field-emission scanning electron microscopy was used to image the ZnO nanowire devices and electrical resistivity measurements were performed. The study is of nanoscale optoelectronic applications.

Krishnankutty, K., John, V.D., 2003. Synthesis, characterization, and antitumour studies of metal chelates of some synthetic curcuminoids. Synth. React. Inorg. Met.-Org. Chem. 33 (2), 343–358, Krishnankutty and John have reported the synthesis of four curcuminoid analogues and their vanadyl(IV), cobalt(II), and copper(II) chelates of ML2 stoichiometry. The complexes were characterized by electronic, IR, ^{1}H NMR, ESR, and mass spectroscopy. The work documented the ease of formation of such chelates.

Liewhiran, C., Seraphin, S., Phanichphant, S., 2006. Synthesis of nano-sized ZnO powders by thermal decomposition of zinc acetate using Broussonetia papyrifera(L) Vent pulp as a dispersant. Matter. Lett. 11, 4–16, Liewhiran et al., claimed the synthesis of nano-sized ZnO powders by thermal decomposition of zinc acetate and Broussonetia papyrifera (L) Ventpulp as a dispersant. The calcined powders were characterized by XRD, SEM, and TEM techniques. The work is an example of green chemistry approach.

Liu, C.H., Zapien, J.A., Yao, Y., Meng, X.M., Lee, C.S., Fan, S.S., Lifshitz, Y., Lee, S.T., 2003. High-density ordered ultraviolet light-emitting ZnO nanowire arrays. Adv. Mater. 15 (10), 838, Liu et al., have grown polycrystalline ZnO nanowires in anodic aluminium oxide templates using a dry vapor deposition method. Luminescence measurements were carried out. The study is of application in semiconductors.

Liu, Y., Zhou, J., Larbot, A., Persin, M., 2007. Preparation and characterization of nano-zinc oxide. J. Mater. Proc. Technol. 189, 379–383, Liu et al., reported the synthesis of ZnO nanocrystals by homogeneous precipitation method using urea and zinc nitrate as raw materials. The as prepared sample was characterized with XRD and SEM techniques, but there is no report on average size of the nanoparticles.

Niassari, M.S., Davar, F., Mazaheri, M., 2005. Preparation of ZnO nanoparticles from [bis(acetylacetonate)Zn(II)oleyl-amine complex by thermal decomposition. Matter. Lett. 59, 2867–2871, Niassari et al., used bis(acetylacetonate) zinc(II) as a precursor to prepare zinc oxide nanoparticles by thermal decomposition. The product was characterized by several techniques that depicted a hexagonal zincite structure. However, the method required different combinations of surfactants.

Park, W.I., Yi, G.C., Kim, D.H., Jung, S.W., 2002. Metalorganic vapour-phase epitaxial growth of vertically well-aligned ZnO nanorods. Appl. Phys. Lett. 80, 4232–4234, Park et al., fabricated ZnO nanorods arrays with a diameter of 40–150 nm on Al_2O_3 substrates. XRD pattern and TEM imaging showed a well ordered wurtzite structure. The observed blue light emission could further be studied.

Purica, M., Budianu, E., Rusu, E., 2001. ZnO thin films on semiconductors substrate for large area photo-detector applications. Thin Solid Films 383 (1–2), 284, Purica et al., reported the deposition of a ZnO thin film on a healed substrate at 400 °C by the thermal decomposition of Zn acetylacetonate. The conductive layers prepared were investigated for photodetector applications. The measured values for the main optoelectrical parameters supported their claims. The method is suitable to increase the sensibility of the conventional photodetectors.

Rensmo, H., Keis, K., Lindstrom, H., Sodergreen, S., Solbrand, A., Hagfeldt, A., Lindquist, S.E., Wang, L.N., Muhammed, M., 1997. High light-to-energy conversion efficiencies for solar cells based on nanostructured ZnO electrodes. J. Phys. Chem. B. 101, 2598, Rensmo et al., investigated the photoelectrochemical properties of nanostructured ZnO thin films electrodes. The overall solar energy conversion efficiency for the film consisting of a 15 nm ZnO particles was 58% compared to 31% for a film consisting of a 150 nm ZnO particles. The results are of high impact and size effect should be further studied.

Senoussaoui, N., Krause, M., Muller, J., 2004. Thin-film solar cells with periodic grating coupler. Thin Solid Films 451–452, 397, Senoussaoui et al., investigated the application of periodic light grating couplers as an alternative to randomly textured transparent conductive oxides by using patterned aluminium dopped ZnO. SEM images of grating were reported. Specular transmission of gratings and total transmission was plotted. More investigations remain to be conducted to establish the use of such alternatives.

Steunou, N., Ribot, F., Boubekeur, K., Maquet, J., Sanchez, C., 1999. Ketones as an oxolation source for the synthesis of titanium-oxo-organo clusters. New J. Chem. 23, 1079–1086, Steunou et al., synthesized two titanium-oxo clusters through the reactions of $Ti(Pr^{i})_4$ ketones such as acetone, acetylacetone and diacetone alcohol. The clusters were studied by ^{17}O, ^{13}C and ^{1}H NMR spectroscopy. Such well defined structure could be used as precursors for metal oxides nanoparticles.

Sun, X.C., Zhang, H.Z., Xu, J., Zhao, Q., Wang, R., Yu, D., 2004. Shape controllable synthesis of ZnO nanorod arrays via vapor phase growth. Solid State Commun. 129 (12), 803, Sun et al., reported the synthesis of ZnO nanorod arrays with peculiar morphologies on silicon substrate via vapor phase growth. It is proved that the morphology depends on the deposition positions relative to the source materials. They supported their claims by XRD and SEM images of hexagonal ZnO crystals. The method could be of general application for engineering the morphology of metal oxides nanomaterials.

Tennesen, H.H., Greenhill, J.V., 1992. Study on curcumin and curcuminoids. Curcumin as a reducing agent and as a radical scavenger. Int. J. Pharm. 87, 79, Tennesen and Greenhill have concluded that the complex formation between curcumin and iron and the reduction of Fe^{3+} to Fe^{2+} in the presence of curcumin are independent of the phenolic hydroxyl groups in the curcumin molecule. The diketone system of curcumin appears to be the part of the molecule involved in the scavenging of oxygen radicals.

Vafaee, M., Ghamsari, M.S., 2007. Preparation and characterization of ZnO nanoparticles by a novel sol–gel route. Mater. Lett. 61, 3265–3268, Vafaee and Ghamsari prepared ZnO nanoparticles with 3–4 nm size using triethanolamine and studied optical property by luminescence spectroscopy. TEM image and XRD pattern were reported. The method is suitable for the synthesis of high photoluminescence spectra.

Vayssieres, L., 2003. Growth of arrayed nanorods and nanowires of ZnO from aqueous solution. Adv. Mater. 15 (5), 464, Vayssieres showed that ZnO could easily be processed as nanowires or arrayed nanorods on solid supports by monitoring the hydrolysis of $Zn(NO_3)_2$. He supported his claim by XRD pattern, SEM and HRTEM images. This study contributes to a low cost manufacturing of nanomaterials.

Wang, C., Shen, E., Wang, E., Gao, L., Kang, Z., Tian, C., Lan, Y., Zhang, C., 2006. Controlable synthesis of ZnO nanoparticles via a surfactant assisted alcohol thermal process at low temperature. Curr. Appl. Phys. 6, 499–502, Wang et al., reported the synthesis of ZnO nano crystals including nanorods by polyvinyl pyrrolidone-assisted solvothermal process. They supported their claims by XRD patterns, TEM images and UV-spectroscopic measurement. The advantage of the method is the use of low temperature.

Wu, C., Qiao, X., Chen, J., Wang, H., Tan, F., Li, S., 2006. A novel chemical route to prepare ZnO nanoparticles. Mater. Lett. 60, 1828, Wu et al., prepared ZnO nanoparticles from $Zn(NO_3)_2{\cdot}6H_2O$ without any requirement of calcinations step at high temperature. A comparative study of chemical reaction from $Zn(NO_3)_2$ to ZnO was given. A study of morphology and luminescence was reported. The method is suitable for a low cost production of nanomaterials.

Xu, C., Xu, G., Liu, Y., Wang, G., 2002. A simple and novel route for the preparation of ZnO nanorods. Solid State Commun. 122, 175–179, Xu et al., reported the synthesis of ZnO nanorods by thermal decomposition of ZnC_2O_4. X-ray diffraction pattern, TEM imaging, Raman spectroscopic measurement, photoelectrons spectroscopy, SAED and HRTEM imaging were used in the study. Results and mechanism reported are of high caliber.

Yan, H., He, R., Johnson, J., Law, M., Saykally, R.J., Yang, P., 2000. Dendritic nanowire ultraviolet laser array. J. Am. Chem. Soc. 125, 4728–4729, Yan et al., synthesized a high yield of microscale comblike structures made of periodic arrays of single-crystalline ZnO nanowires applying a chemical vapor transport and condensation system. SEM images showed the comb structures. The X-ray diffraction confirmed the wurtzite structure. TEM images and a lattice spacing of 2.56 ± 0.05 Å were reported. These nanowire arrays could have applications as one-dimentional photonic crystals.

Zhang, H., Ma, X.Y., Xu, J., Niu, J., Yang, D., 2003. Arrays of ZnO nanowires fabricated by a simple chemical solution route. Nanotechnology 14 (4), 423, Zhang et al., have synthesized ZnO nanorods by evaporating ZnO powder. The morphology of the nano particles is well documented. Although the thermal evaporation method is simple experimentally but it requires high temperature and involves the formation of intermediate precursors.