Optical properties of composite structure based on ZnO microneedles and Alq₃ thin film

I. Karbovnyk¹ · B. Sadoviy¹ · B. Turko¹ · A. M. Kostruba² · A. Luchechko¹ · V. S. Vasil’yev¹ · R. Serkiz¹ · Y. Kulyk¹ · H. Klym³ · P. K. Khanna⁴ · A. V. Kukhta⁵

Abstract

The composite material based on ZnO microneedles and Alq₃ thin film has been obtained. The photoluminescence study shows a tenfold enhancement in the band-edge UV emission (390 nm) of ZnO microneedles and 2× enhancement in visible emission of the hybrid composite, when excited by 266 nm laser beam. This enhancement can be explained by the interaction between ZnO and Alq₃ molecules and the energy transfer from ZnO to Alq₃ molecule. Discussed composite structures can find interesting applications as emitting layers in OLED devices.

Keywords Tris-(8-hydroxyquinoline)aluminum · Zinc Oxide · Composite · Photoluminescence · Energy Transfer

1 Introduction

Organic light-emitting diode (OLED) technologies are at the center of attention of scientists working in the field of optoelectronics, due to their wide practical use. The serious problems of OLED based devices such as degradation of properties due to the influence of oxygen and water molecules, relatively low glass transition temperatures, low mobility of charge carriers due to the amorphous nature of solids made from organic molecules remain unsolved (Buckley 2013). Besides, the problem to obtain white light is simply still actual (Yongming Yin et al. 2019). One of the promising ways to address these problems is the use of nanocomposites to create hybrid organic–inorganic LEDs. To optimize such hybrid
systems with controlled optoelectronic properties, it is necessary and important to have a deep understanding of the processes of electronic energy transfer between organic and inorganic subsystems (Manzhia et al. 2019).

Tris(8-hydroxyquinoline)aluminium (Alq3) is a very stable and widely used electron-transport and light emitting material in organic optoelectronic devices (Fung et al. 2012). This material is thermally stable, has a high glass-transition temperature of 172 °C, and can easily be thermally deposited to form pin hole–free amorphous thin films due to its intrinsic polymorphic phase behavior (Li 2015). Semiconductor materials based on ZnO are now considered as the best alternative to indium tin oxide, since they are much cheaper and non-toxic (Kapustianyk et al. 2015). This material is also light emitting (Kapustianyk et al. 2014). There are many companies in the world involved into production of transparent and electrically conductive ZnO-based oxides for the needs of electronics (Turko et al. 2021). The most challenging problem of the electrooptic devices based on ZnO homojunction is the lack of stable and reliable $p$-type doping (Kapustianyk et al. 2014). In this situation, ZnO-based LEDs usually are fabricated by combining of $n$-type ZnO with a $p$-type semiconductor other than ZnO, for example, Cu$_2$O, ZnTe, SrCu$_2$O$_2$, AlGaN, GaN or $p$-type conduction polymers (Kapustianyk et al. 2014; Turko et al. 2019). To our knowledge, there are quite a number of publications devoted separately to ZnO and Alq3, while composite materials based on them have been studied by only a few research teams from India (Cuba et al. 2014; Cuba and Muralidharan 2014, 2015; Dasi et al. 2018, 2020; Uthirakumar et al. 2008), China (Kan et al. 2011; Lv et al. 2016), Swiss (Sanchez-Valencia et al. 2016), Republic of Korea (Lee et al. 2010) and Japan (Iechi et al. 2004). They consider different combinations of this composite such as amorphous or polycrystalline AlQ$_3$ or ZnO doped with ZnO (Cuba et al. 2014; Cuba and Muralidharan 2014, 2015) or AlQ$_3$ (Dasi et al. 2018, 2020), composite nanowires (Lee et al. 2010), heterostructures (Kan et al. 2011; Lv et al. 2016; Iechi et al. 2004), or AlQ$_3$ imbedded into porous ZnO (Uthirakumar et al. 2008; Sanchez-Valencia et al. 2016), and enhancement of photoluminescence intensity of AlQ$_3$ and ZnO has been observed. Researchers also focus on the study of linear, nonlinear and photophysical properties of ZnO and Alq3 thin films (Kulyk et al. 2007; Zawadzka et al. 2013), as well as on specifics of their preparation and practical applications (Zawadzka et al. 2014; Harun et al. 2017).

In this paper, we report the data concerning fabrication and luminescent properties of the composite structure based on ZnO microneedles and Alq3 thin film.

2 Experimental

The ZnO microneedles were obtained on Si (100) substrates by a solid–vapor-phase process in a horizontal tube furnace at a heating temperature of 500 °C in air atmosphere using pure metallic Zn powder (> 98% purity) (Turko et al. 2012; Cheng et al. 2014).

Alq3 organic layers with the thickness less than 50 nm were thermally deposited in $10^{-4}$ Pa vacuum on Si substrates without, and, for composite structure fabrication, covered by ZnO microneedles. Alq3 powder (99.995% purity) was purchased from Sigma-Aldrich Corporation and purified by recrystallization. Thickness control during the process was provided by quartz crystal deposition rate controller.

The X-ray diffraction (XRD) measurements were carried out using STOE STADI P diffractometer with linear position sensitive detector in transmission Bragg–Brentano
Optical properties of composite structure based on ZnO…

The surface morphology and the local chemical composition of the samples were analyzed using a PEMMA-102–02 (SELMI, Ukraine) scanning electron microscope.

The photoluminescence (PL) spectra were measured using a portable fiber optic spectrometer AvaSpec-ULS2048L-USB2-UA-RS (Avantes BV, (Apeldoorn, Netherlands) with an input slit of 25 μm, a diffraction grating of 300 lines/mm and a resolution of 1.2 nm. The accumulation time was 1000 ms. The samples were excited by Nd:YAG laser (266 nm, max output power – 1 μJ, light spot diameter ~1 mm, pulse duration < 1 ns, max repetition rate – 10 kHz).

3 Results and discussion

Up to now, various growth approaches have been used for the synthesis of Alq3 nano- or microstructures (Xie et al. 2014; Kim et al. 2018; Bi et al. 2010; Horike et al. 2016; Cui et al. 2013; Park et al. 2020; Khan et al. 2019; Lo et al. 2012; Wang et al. 2016). Partially, different variants of vacuum evaporation of Alq3 have resulted in the creation of fine nanowires and microcrystals with a clear hexagonal morphology (Xie et al. 2014; Horike et al. 2016; Khan et al. 2019). The problem is that Alq3 molecule has two different geometric isomers: meridional (mer-) and facial (fac-) (Xie et al. 2014). Five crystalline phases of Alq3, α-, β-, γ-, δ- and ε- have been observed (Xie et al. 2014). α- and β- phases have two mer-Alq3 molecules in a unit cell, while δ-phase has four fac-Alq3 per unit cell (Xie et al. 2014). Also, the morphology of vacuum deposited organic films depends strongly on the substrate (Kukhta et al. 2009). Zinc oxide nanostructure was employed as catalyst in organic syntheses and transformations (Hosseini-Sarvari 2013). ZnO microneedles can be expected to act as catalysts and nucleation centres for the growth of specific Alq3 structures.

X-ray diffraction pattern of the initial Alq3 powder is shown in Fig. 1. The X-ray diffraction analysis of OLEDs materials, including Alq3, is often rather difficult, because the crystals of OLEDs materials are sometimes disordered and contaminated by other polymorphs. We compared this pattern with the XRD patterns of α-, β-, γ-, δ- and ε-Alq3 (Cui et al. 2013; Park et al. 2020; Brinkmann et al. 2000; Braun et al. 2001; Colle and Brutting 2005; Rajeswaran et al. 2009). The powder exhibits quite similar XRD pattern to that of α-phase Alq3. This is important to know since photoluminescence properties for different phases of Alq3 may vary.

The morphology of the investigated ZnO microneedles and ZnO-Alq3 composite is presented in Fig. 2. ZnO microneedles with an average diameter of about 0.5–6 μm and height of ~4 μm were grown on the (100) silicon substrate. Figure 2, a confirm the hexagonal nature of grown ZnO structures. The morphology of Alq3 film deposited on ZnO microneedles is presented in Fig. 2, b. These structures with the thickness of 50 nm seem to cover outside surfaces of ZnO microneedles.

The room-temperature PL spectrum of the ZnO microneedles (Fig. 3) consists of the two weak bands in the ultraviolet (UV) and visible regions. The UV band at 390 nm is typical for ZnO and arises due to recombination of the free excitons, bound excitons and transitions in the donor–acceptor pairs (Kapustianyk et al. 2016). The wide green band in
the range from approximately 450 nm to 650 nm is caused by defects, first of all, by uncontrolled impurities and stoichiometry defects (Kapustianyk et al. 2016).

The room-temperature PL emission spectrum of pure Alq₃ film with the same thickness as in composite film (they were obtained at the same deposition process) exhibits a characteristic green emission at around 525 nm (Park et al. 2020; Xu et al. 2006) when excited at 266 nm is shown in Fig. 3. Alq₃ is characterized by crystallization in polymorphism both under vapor deposition and solvent evaporation (Wang et al. 2016).

As you can see in Fig. 3, the intensity of the UV PL band of the composite is more than 10 times higher than that of ZnO microneedles, and the intensity of the band with a maximum at 525 nm is approximately twice as high than that of this band in the PL spectrum of the Alq₃ thin film. It can be seen that both bands are not relatively narrow and shoulders of both bands do not increase the intensity of each other. Our results correlate satisfactorily with the data reported in Refs. Cuba et al. (2014), Cuba and Muralidharan (2014, 2015) and Dasi et al. 2020). According to that data, compared with PL of pure Alq₃ and ZnO, PL of the composite sample based on ZnO and Alq₃ has higher intensities due to the processes of energy transfer between inorganic and organic materials. According to Dasi et al. (2020), when composite material based on ZnO and Alq₃ is excited with 266 nm wavelength, both ZnO and Alq₃ molecules are excited simultaneously. The excited state energy of Alq₃ molecule can be absorbed by the luminescent quencher and then the absorbed energy may eventually be non-radiatively transferred to ZnO, giving rise to an increase in UV emission (band edge emission) of ZnO in the composite.

However, in the case of the energy transfer the luminescence intensity of component from which energy transfer occurs, has to be decreased. But, in our case, the luminescence enhancement of ZnO and Alq₃ is observed in both bands. To address the question about energy transfer between inorganic and organic counterparts in our system, excitation functions of Alq₃ and the composite have been measured (see Fig. 4). They characterize the efficiency of energy transformation in the considered system, taking into account the efficiency of absorption, luminescence quantum yield, and luminescence spectrum shift. In

![X-ray diffraction profile of the original Alq₃ powder](image-url)
the case of the absence of changes in quantum yield and spectral shifts, excitation functions correspond to the absorption spectra. The shape of the obtained function for pure Alq3 is similar to the reported literature (Baldacchini et al. 2002). In the excitation function of the composite both components can be excited simultaneously (Fig. 4). Probability of excitations is changed over the spectrum, as a result the ratio of the enhanced emission will depend on the excitation wavelength. Since no emission of Alq3 in the region of 390 nm is observed, curve 3 in Fig. 4 belongs only to radiation of ZnO microneedles. The energy in the region of 390 nm ZnO band can be transferred to Alq3. However, comparing energy diagrams of ZnO (4.2 and 7.6 eV (Gupta et al. 2011)) and Alq3 (3.2 and 5.7 eV (Hellstrom et al. 2008)), it can be seen that conditions for energy transfer from Alq3 to ZnO UV band and even from this ZnO band to Alq3 are not appropriate. Nevertheless, the radiative energy transfer can be observed, when Alq3 absorbs UV luminescence of ZnO. But, luminescence lifetime of ZnO UV band (1.56 ns) (Sonmez and Meral 2012) is an order of magnitude less than that of Alq3 (12 ns) (Tang et al. 2000). As a result, this process can’t be efficient. The shape of excitation function registered at 520 nm is slightly differed for composite as compared to pure Alq3 film. It means that some energy transfer from ZnO green band to Alq3 occurs. It can be noted that some difference in PL intensity of Alq3 band may
also be due to the difference in Alq3 morphology (pure Alq3 film is amorphous and Alq3 in composite may form specific structures with higher quantum yield). No evidence of energy transfer from Alq3 to ZnO is observed.

On the other side, the observed enhancement of luminescence intensity of both components under Alq3 deposition can be caused by mutual influence of each other. It has

---

**Fig. 3** Room-temperature PL emission spectra of Alq3 thin film, ZnO microneedles and composite structure based on ZnO microneedles and Alq3 thin film

**Fig. 4** Normalized excitation functions of Alq3 (1) and Alq3 + ZnO (2, 3) film (registration at 520 (1, 2) and 390 (3) nm)
been found that passivation of ZnO films by coatings with metal oxides (Lapp et al. 2020) and doping with hydrogen (Huang et al. 2012) result in the strong UV ZnO luminescence enhancement. Alq3 contains oxygen atoms and a lot of hydrogen atoms to promote this process. Besides, interaction of Zn ions with Alq3 was found to enhance luminescence of Alq3 (Khan et al. 2019). The luminescence intensity of green band is also enhanced that can be noticed from the shape changes of Alq3 band.

4 Conclusion

The composite material based on ZnO microneedles and Alq3 thin film has been synthesized. It is shown that Alq3 film deposited on ZnO microneedles with the thickness of 50 nm covers their surface. The photoluminescence study shows a tenfold enhancement in the band-edge UV emission (390 nm) of ZnO and doubled intensity of the visible emission in the hybrid composite, when excited by 266 nm wavelength. Probability of excitations is changed over spectrum, as a result the ratio of the enhanced emission depends strongly on the excitation wavelength. This enhancement can be explained by the interaction between ZnO and Alq3 molecules, and the energy transfer from ZnO to Alq3 molecule. This composite is a possible candidate for the emitting layer of an OLED device.

Acknowledgements This research work was supported by National Research Foundation of Ukraine in the frame of the project 2020.02/0217 “Light-generating low-dimensional structures with polarized luminescence based on organic and inorganic materials”.

References

Baldacchini, G., Gagliardi, S., Montereali, R.M., Pace, A., Pode, R.B.: Optical spectroscopy of tris(8-hydroxyquinoline) aluminium thin films. Phy. Mag. B 82(6), 669–680 (2002). https://doi.org/10.1080/13642810110038386

Bi, H., Zhang, H., Zhang, Y., Gao, H., Su, Z., Wang, Y.: Fac-Alq3 and mer-Alq3 nano/microcrystals with different emission and charge-transporting properties. Adv. Mater. 22, 1631–1634 (2010)

Braun, M., Gmeiner, J., Tzolov, M., Coelle, M., Meyer, F.D., Milius, W., Hillebrecht, H., Wendland, O., von Schutz, J.U., Brütting, W.: A new crystalline phase of the electroluminescent material tris(8-hydroxyquinoline) aluminium exhibiting blueshifted fluorescence. J. Chem. Phys. 114, 9625–9632 (2001)

Brinkmann, M., Gadret, G., Muccini, M., Taliani, C., Masciochi, N., Sironi, A.: Correlation between molecular packing and optical properties in different crystalline polymorphs and amorphous thin films of mer-Tris(8-hydroxyquinoline)aluminium(III). J. Am. Chem. Soc. 122, 5147–5157 (2000)

Buckley, A.: Organic Light-Emitting Diodes (OLEDs): Materials, Devices and Applications, p. 666. Woodhead Publishing Limited (2013)

Cheng, J., Yang, X., Tian, H., Zhao, B., Zhang, D.: Catalyst-free synthesis of hollow-sphere-like ZnO and its photoluminescence property. Adv. Mater. Sci. Eng. 2014, 567278 (2014)

Colle, M., Brütting, W.: Chapter 4: Thermal and Structural Properties of the Organic Semiconductor Alq3 and Characterization of Its Excited Electronic Triplet State. In book: Physics of Organic Semiconductors. Weinheim: Wiley-VCH Verlag GmbH & Co. KgaA, p. 536 (2005)

Cuba, M., Muralidharan, G.: Enhanced luminescence properties of hybrid Alq3/ZnO (organic/inorganic) composite films. J. Lumin. 156, 1–7 (2014)

Cuba, M., Muralidharan, G.: Improved luminescence intensity and stability of thermal annealed ZnO incorporated Alq3 composite films. J. Fluoresc. 25, 1629–1635 (2015)

Cuba, M., Rathinavalli, U., Thangaraju, K., Muralidharan, G.: Synthesis and optical properties of ZnO incorporated tris-(8-hydroxyquinoline)aluminum. J. Lumin. 153, 188–193 (2014)

Cui, C., Park, D.H., Kim, J., Joo, J., Ahn, D.J.: Oligonucleotide assisted light-emitting Alq3 microrods: energy transfer effect with fluorescent dyes. Chem. Commun. 49, 5360–5362 (2013)
Dasi, G., Ramarajan, R., Paul Joseph, D., Vijayakumar, S., Shim, J.-I., Arivananthan, M., Jayavel, R., Thangaraju, K.: Enhanced UV emission of solution processed highly transparent Alq3/ZnO hybrid thin films. Thin Solid Films 710, 138265 (2020)

Dasi, G., Ramarajan, R., Thangaraju, K.: Improved electron injection in spin coated Alq3 incorporated ZnO thin film in the device for solution processed OLEDs. Journal of Applied Physics. Conference Proceedings 1942, 060015 (2018)

Fung, M.K., Ching Ng, A.M., Djurisic, A.B., Chan, W.K., Wang, H.: Preparation of 8-hydroxyquinoline wires by decomposition of tris(8-hydroxyquinoline)aluminium. J. Exp. Nanosci. 7, 578–585 (2012)

Gupta, R.B., Nagpal, S., Arora, S., Bhatnagar, P.K., Mathur, P.C.: Ultraviolet electroluminescence from zinc oxide nanorods/deoxyribonucleic acid hybrid bio light-emitting diode. J. Nanophotonics 5, 059505 (2011)

Harun, K., Hussain, F., Purwanto, A., Sahraoui, B., Zawadzka, A., Mohammad, A.A.: Sol–gel synthesized ZnO for optoelectronics applications: a characterization review. Mater. Res. Express 4(12), 122001 (2017)

Hellstrom, S.L., Ugozott, J., Britovsek, G.J.P., Jones, T.S., White, A.J.P.: The Effect of Fluorination on the Luminescent Behaviour of 8-Hydroxyquinoline Boron Compound. New J. Chem. 32, 1379–1387 (2008)

Horike, S., Misaki, M., Koshiba, Y., Morimoto, M., Ishida, K.: Unique morphology and optical properties of tris(8-hydroxyquinoline)aluminum crystal grown by ionic liquid-assisted vacuum vapor deposition. Chem. Lett. 45, 1156–1158 (2016)

Hosseini-Sarvari, M.: Catalytic organic reactions on ZnO. Curr. Org. Synth. 10, 697–723 (2013)

Huang, X.H., Zhan, Z.Y., Pramoda, K.P., Zhang, C., Zheng, L.X., Chua, S.J.: Correlating the enhancement of UV luminescence from solution-grown ZnO nanorods with hydrogen doping. CrystEngComm 14, 5163–5165 (2012)

Iechi, H., Sakai, M., Nakamura, M., Kudo, K.: Vertical type organic light emitting transistor using thin-film ZnO. Book of abstracts International conference on solid state devices and materials, 15–17 September, 2004. Tokyo, Japan, P. 164–165 (2004)

Kan, P., Wang, Y., Zhao, S., Xu, Z., Wang, D.: Electroluminescence dependence on the organic thickness in ZnO nano rods/Alq3 heterostructure devices. J. Nanosci. Nanotechnol. 11, 3470–3473 (2011)

Kapustianyk, V., Turko, B., Luzinov, I., Rudyk, V., Tsybulskiy, V., Balyshyn, S., Rudyk, Yu., Savchak, M.: LEDs based on p-type ZnO nanowires synthesized by electrochemical deposition method. Phys. Status Solidi C 11, 1501–1504 (2014)

Kapustianyk, V.B., Turko, B.I., Rudyk, V.P., Kulyk, B.Y., Rudko, M.S.: Effect of dopants and surface morphology on the absorption edge of ZnO films doped with In, Al, and Ga. J. Appl. Spectrosc. 82, 153–156 (2015)

Kapustianyk, V., Turko, B., Rudyk, V., Rudyk, M., Panasiuk, M., Serkiz, R.: Effect of vacuumization on the photoluminescence and photoresponse decay of the zinc oxide nanostructures grown by different methods. Opt. Mater. 56, 71–74 (2016)

Khan, M.B., Ahmad, S., Azim, M., Salah, N., Khan, Z.H.: Highly luminescent Alq3: Zn nanowires. Mater. Res. Express 6, 105052 (2019)

Kim, S., Kim, D.H., Choi, J., Lee, H., Kim, S.-Y., Park, J.W., Park, D.H.: Growth and brilliant photo-emission of crystalline hexagonal column of Alq3 microwires. Materials 11, 472 (2018)

Kukhta, A.V., Kukhta, I.N., Kolesnik, E.E., Olkhovik, V., Galinovskii, N.A., Javnerko, G.K.: Spectroscopic and morphological properties of dibenzoxazolyl biphenyl thin films. J. Fluoresc. 19(6), 989–996 (2009). https://doi.org/10.1007/s10895-009-0498-3

Kulyk, B., Essaidi, Z., Luc, J., Soifian, Z., Boudebs, G., Sahraoui, B., Kapustianyk, V., Turko, B.: Second order and third order nonlinear optical properties of microrod ZnO films deposited on sapphire substrates by thermal oxidation of metallic zinc. J. Appl. Phys. 102(11), 113113 (2007)

Lapp, J., Thapa, D., Huso, J., Canul, A., Norton, M.G., McCluskey, M.D., Bergman, L.: Enhancement of the ultraviolet photoluminescence of ZnO films: Coatings, annealing, and environmental exposure studies. AIP Adv. 10, 085217 (2020). https://doi.org/10.1063/5.0016510

Lee, J.H., Shin, J.H., Song, J.Y., Yi, Y.: Interface formation between tris(8-hydroxyquinoline)aluminum and ZnO nanowires and film. Appl. Phys. Lett. 97, 263302 (2010)

Li, Z.R.: Organic Light-Emitting Materials and Devices, 2nd Edition. Taylor & Francis Group, LLC, p. 813 (2015)

Lo, S.-S., Hsu, W.-H., Sie, S.-H., Leu, H.-J.: A single Alq3 submicro-wire Schottky diode and its negative differential resistance. J. Mater. Chem. 22, 12618–12621 (2012)

Lv, X., Wang, H., Meng, L., Wei, X., Chen, Y., Kong, X., Liu, J., Tang, J., Wang, P., Wang, Y.: Highly efficient inverted organic light-emitting diodes based on thermally activated delayed fluorescence. Sci. China Mater 59, 421–426 (2016)
Manzhia, P., Kumari, R., Alam, M.B., Umapathy, G.R., Krishna, R., Ojha, S., Srivastava, R., Sinhaa, O.P.: Mg-doped ZnO nanostructures for efficient Organic Light Emitting Diode. Vacuum 166, 370–376 (2019)

Park, J., Kim, S., Choi, J., Yoo, S.H., Oh, S., Kim, D.H., Park, D.H.: Fine fabrication and optical waveguide characteristics of hexagonal tris(8-hydroxyquinoline)aluminium (III) (Alq3) crystal. Curr. Comput.-Aided Drug Des. 10, 260 (2020)

Rajeswaran, M., Blanton, T.N., Tang, C.W., Lenhart, W.C., Switalski, S.C., Giesen, D.J., Antalek, B.J., Pawlik, T.D., Kondakov, D.Y., Zumbulyadis, N., Young, R.H.: Structural, thermal, and spectral characterization of the different crystalline forms of Alq3, tris(quinolin-8-olato)aluminium(III), an electroluminescent material in OLED. Polyhedron 28, 835–843 (2009)

Sanchez-Valencia, J.R., Longtin, R., Rossell, M.D., Gröning, P.: Growth assisted by glancing angle deposition: a new technique to fabricate highly porous anisotropic thin films. ACS Appl. Mater. Interfaces 8, 8686–8693 (2016)

Sonmez, E., Meral, K.: Enhancement of Photoluminescence Lifetimes of ZnO Nanorods Making Use of Thiourea. J. Nanomat. 33, 957035 (2012). https://doi.org/10.1155/2012/957035

Tang, K.-C., Cheng, P.-W., Chien, V., Cheng, C.P., Cheng, P.-Y., I-Chia Chen.: Fluorescence Lifetime of Tris-(8-Hydroquinoline) Aluminium Thin Film and Solution. J. Chin. Chem. Soc. 47, 875–879 (2000). https://doi.org/10.1002/jccs.20000118

Turko, B., Nikolenko, A., Sadovyi, B., Toporovska, L., Rudko, M., Kapustianyk, V., Strelchuk, V., Panasyuk, M., Serkiz, R., Demchenko, P.: Electroluminescence from n-ZnO microdisks/p-GaN heterostructure. Opt. Quant. Electron. 51, 135 (2019)

Turko, B., Mostovoy, U., Kovalenko, M., Elyashhevskyi, Y., Kulyk, Y., Bovgrya, O., Dzikovskyi, V., Kostruba, A., Vlokh, R., Savaryn, V., Stybel, V., Tsizh, B., Majevska, S.: Effect of dopant concentration and crystalline structure on the absorption edge in ZnO: Y films. Ukr. J. Phys. Opt. 22, 31–37 (2021)

Turko B.I., Len, N.V., Kapustianyk, V.B.: The method of obtaining ZnO nanostructures. Patent UA No 71235 (Ukr) (2012)

Uthirakumar, P., Suh, E.-K., Hong, C.-H.: Growth, morphology and optical properties of tris(8-hydroxyquinoline)aluminium/zinc oxide hybrid nanowires. J. Lumin. 128, 1629–1634 (2008)

Wang, Y.Y., Ren, Y., Liu, J., Zhang, C.Q., Xia, S.Q., Tao, X.T.: Crystal growth, structure and optical properties of solvated crystalline Tris(8-hydroxyquinoline)aluminium (III) (Alq3). Dyes Pigm. 133, 9–15 (2016)

Xie, W., Pang, Z., Zhao, Y., Jiang, F., Yuan, H., Song, H., Han, S.: Structural and optical properties of e-phase tris(8-hydroxyquinoline) aluminium crystals prepared by using physical vapour deposition method. J. Cryst. Growth 404, 164–167 (2014)

Xu, Y.F., Zhang, H.J., Li, H.Y., Bao, S.N., He, P.: Photoluminescence spectroscopy study on tris (8-hydroxyquinoline) aluminium film. Appl. Surf. Sci. 252, 2328–2333 (2006)

Yongming Yin, M.U., Ali, W.X., Yang, H., Meng, H.: Evolution of white organic light-emitting devices: from academic research to lighting and display applications. Mater. Chem. Front. 3, 970–1031 (2019). https://doi.org/10.1039/C9QM00042A

Zawadzka, A., Płociennik, P., Strzelecki, J., Łukasiak, Z., Sahraoui, B.: Photophysical properties of Alq3 thin films. Opt. Mater. 36(1), 91–97 (2013)

Zawadzka, A., Płociennik, P., Strzelecki, J., Sahraoui, B.: Transparent amorphous zinc oxide thin films for NLO applications. Opt. Mater. 37, 327–337 (2014)

Zawadzka, A., Płociennik, P., El Kouari, Y., Bougharraf, H., Sahraoui, B.: Linear and nonlinear optical properties of ZnO thin films deposited by pulsed laser deposition. J. Lumin. 169, 483–491 (2016)

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.