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Preparation and Dielectric Properties of Polymer Nanocomposites for Dielectric Applications

Majeed Ali Habeeb[1], Rehab Shather Abdul Hamza[1], and Idrees Oreibi[2]

[1]*College of Education for Pure Sciences,*
Department of Physics,
University of Babylon,
Hillah, Iraq
[2]*Directorate of Education Babylon,*
Ministry of Education,
Babylon, Iraq

The nanocomposites consisting of polyvinyl alcohol (PVA), zirconium dioxide (ZrO_2) and copper oxide (CuO) nanoparticles are synthesized using the solution cast method. The samples including PVA (acting as the organic host matrix) together with varying quantities of nanoparticles of zirconium dioxide (ZrO_2) and copper oxide (CuO) ranging from 0 to 6 wt.%. The present work examines the electrical characteristics of PVA–ZrO_2–CuO nanocomposites. The investigation is focused on the electrical properties of nanocomposites within the frequency range from 100 Hz to $5{\cdot}10^6$ Hz, while maintaining ambient temperature conditions. The experimental results demonstrate that the dielectric constant and dielectric loss of the PVA–ZrO_2–CuO nanocomposites are decreased with increasing frequency of the applied electric field. The electrical conductivity of alternating current (A.C.) positively correlates with the current frequency. The contents of the PVA–ZrO_2–CuO nanocomposites positively correlate with pure PVA dielectric constant, dielectric loss, and A.C. electrical conductivity. The decisive results suggest that the nanostructures composed of PVA–ZrO_2–CuO possess promising prospects for utilization in a wide range of electrical and electronic nanodevices.

Нанокомпозити, що складаються з полівінілового спирту (ПВС), наночастинок діоксиду Цирконію (ZrO_2) й оксиду Купруму (CuO), синтезовано методом лиття розчину. Зразки містили ПВС, який діяв як органічна матриця-господар, разом із різними кількостями наночастинок ZrO_2 і CuO у межах від 0 до 6 мас.%. У даній роботі досліджено електричні характеристики нанокомпозитів ПВС–ZrO_2–CuO. Дослідження зосереджено на електричних властивостях нанокомпозитів у діяпазоні частот від 100 Гц до $5{\cdot}10^6$ Гц з дотриманням температурних умов на-

вколишнього середовища. Результати експерименту показують, що діелектрична проникність і діелектричні втрати нанокомпозитів ПВС–ZrO_2–CuO зменшуються зі збільшенням частоти прикладеного електричного поля. Електропровідність змінного струму (А.С.) позитивно корелює з частотою струму. Вміст нанокомпозитів ПВС–ZrO_2–CuO позитивно корелює з діелектричною проникністю, діелектричними втратами й електропровідністю змінного струму для чистого ПВС. Вирішальні результати свідчать про те, що наноструктури, які складаються з ПВС–ZrO_2–CuO, мають багатообіцяючі перспективи для використання в широкому діяпазоні електричних і електронних нанопристроїв.

Key words: PVA, ZrO_2–CuO nanoparticles, nanocomposites, electrical properties, nanodevices.

Ключові слова: полівініловий спирт, наночастинки ZrO_2–CuO, нанокомпозити, електричні властивості, нанопристрої.

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1. INTRODUCTION

Materials science and technological revolution are underway, and at their centre are polymers. The science of polymers and technology has progressed highly over the last few decades [1, 2]. Polymers with corrosion resistance, low weight, and strong hardness make various products, including homemade plastics, automobile internal and external components, biomedical equipment, and satellite applications [3, 4]. A polymer blend refers to the amalgamation of two or more polymers, forming a novel material exhibiting distinct physical characteristics. Polymer mixtures, known as heat mixes, are a specific category within the broader classification of polymer mixtures. The phenomenon of heat mixing and the behaviour of thermoplastic heat mixtures have been extensively investigated in scientific research [5, 6].

Polyvinyl alcohol (PVA) has emerged as a favourable host matrix for a range of metal oxide nanofillers due to its biodegradability, ability to form films, ease of processing, lack of toxicity, optical transparency, minimal light scattering with a low refractive index, and impressive mechanical properties [7, 8]. PVA is a water-soluble synthetic polymer that comes as a granular powder that is odourless, translucent, tasteless, and white or cream in colour. Since PVA is water-soluble, it can be used to make hydroxyl organic ingredients. The PVA biological degradation and biocompatibility are two of its most notable characteristics. PVA has a high tensile strength and longevity and a high oxygen and scent buffer. Visual light transmission is excellent. It also has excellent shape, mixing, and adhesion characteristics [9, 10]. PVA is com-

monly subjected to annealing processes involving several low-molecular-weight chemicals, typically exhibiting polar functional groups. The groups above establish hydrogen bonds with the hydroxyl groups of the PVA chain, irrespective of the presence or absence of water. As a result, direct hydrogen bonding is reduced among the more considerable PVA molecules [11, 12].

The scientific community has shown considerable interest in wide-bandgap metal-oxide nanoparticles owing to their versatile applications. Zirconium dioxide (ZrO_2) possesses remarkable chemical and physical attributes, which render it suitable for various applications. These include but are not limited to fuel cells, catalysts, optoelectronics, gas sensors, and materials resistant to corrosion [13, 14]. ZrO_2 has a band gap of over 5 eV, making it a significant luminous material characterized by favourable optical transparency. Moreover, its considerable surface area and abundant oxygen vacancies establish it as a promising contender for photocatalytic purposes. The substance is characterized by three distinct crystal phases: tetragonal, monoclinic, and cubic. The presence of these polymorphs is contingent upon factors such as the synthesis procedure, particle dimensions, calcination temperature, and the occurrence of flaws [15, 16].

Metal-oxide nanoparticles, such as copper oxide (CuO), have garnered significant interest primarily due to their antibacterial and biocidal characteristics, rendering them potentially valuable in numerous biomedical applications [17, 18]. CuO is categorized as a semi-conductor metal owing to its unique optical, electrical, and magnetic properties. This material has many uses in creating supercapacitors, sensors, magnetic storage media, near-infrared filters, catalysis, and semiconductors [19, 20]. Copper oxide nanoparticles (CuO NPs) have been employed to enhance polymer films derived from petroleum-based or bio-based sources; this is due to the notable attributes of CuO NPs, including their substantial surface-to-volume ratio, relatively low toxicity, thermal stability, and capacity to reinforce the mechanical properties of polymers [21, 22].

2. MATERIALS AND METHODS

Nanocomposite films were fabricated using the casting technique, incorporating PVA, ZrO_2 and CuO nanoparticles. The experimental procedure entailed dissolving pure PVA in 40 ml of distilled water over 45 minutes. During this process, a magnetic stirrer facilitated stirring at 50°C, promoting a more uniform and homogeneous solution. The polymer underwent the incorporation of the ZrO_2 and CuO nanoparticles at different weight percentages: 0%, 2%, 4%, and 6%. Following four days of air-drying the solution at ambient conditions, the outcome observed was the practical synthesis of poly-

mer nanocomposites. The nanocomposites (NCs) consisting of PVA–ZrO_2–CuO were obtained from the Petri dish and utilized for measurement. The dielectric properties of nanocomposites were assessed using an LCR metre of the HIOKI 3532-50 LCR HI TESTER type across a frequency range spanning from 100 Hz to 5 MHz.

In order to determine the dielectric constant (ε'), one may employ the following formula [23]:

$$\varepsilon' = C_p/C_0, \tag{1}$$

where C_p signifies capacitance, while C_0 denotes a vacuum capacitor.

Dielectric loss (ε'') is given by [24]:

$$\varepsilon'' = \varepsilon' D, \tag{2}$$

where D is the dispersion factor.

The A.C. electrical conductivity is calculated as follows [25, 26]:

$$\sigma_{\text{A.C.}} = \omega\varepsilon_0\varepsilon'', \tag{3}$$

where ω is the angular frequency.

3. RESULTS AND DISCUSSION

Figure 1 depicts the frequency-dependent changes in the dielectric constant of nanocomposites composed of PVA, ZrO_2, and CuO, denoted as PVA–ZrO_2–CuO nanocomposites. The findings indicate that the dielectric constant decreases as the applied electrical-field frequency (F) increases across all samples. At lower frequencies, the insulating materials' dipoles, formed as a response to the application of alternating current, demonstrate a propensity to orient themselves in alignment with the direction of the applied electric field. This alignment causes a charge build-up, resulting in heightened polarisation and an elevated dielectric constant [27, 28].

At high frequencies, the dipoles cannot keep up with the direction of movement of the applied electric field due to the shorter time available for the dipoles to align, which leads to a decrease in polarization and, thus, a decrease in the dielectric constant value. This feature can be used in many applications, such as communication antennas and microwave components [29, 30].

Figure 2 illustrates the frequency-dependent dielectric loss of nanocomposites composed of PVA, ZrO_2, and CuO. According to the data presented in the graph, it can be observed that an increase in frequency is associated with a decrease in dielectric loss.

The phenomena under consideration are attributed to mobile

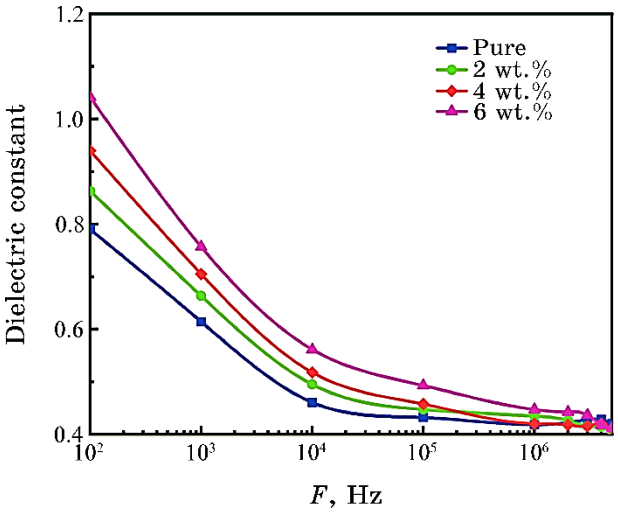

Fig. 1. Behaviour of ε′ with frequency of PVA–ZrO_2–CuO NCs.

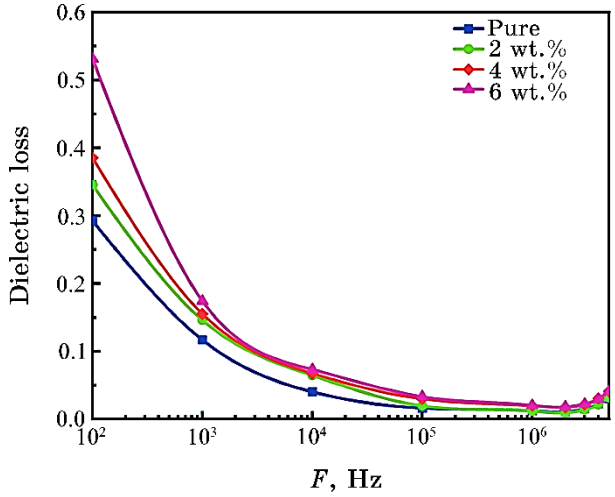

Fig. 2. Behaviour of ε″ with frequency of PVA–ZrO_2–CuO NCs.

charges inside the polymer backbone. The occurrence results from reducing the contribution of space charge polarisation with increasing frequency [31, 32]. The dielectric loss for PVA–ZrO_2–CuO nanocomposites exhibits an increase due to an elevated quantity of electrons, particularly at moderate frequencies, but diminishes as the frequency is elevated [33, 34].

Figures 3 and 4 depict the relationship between the concentrations of NPs and the dielectric constant as well as the dielectric

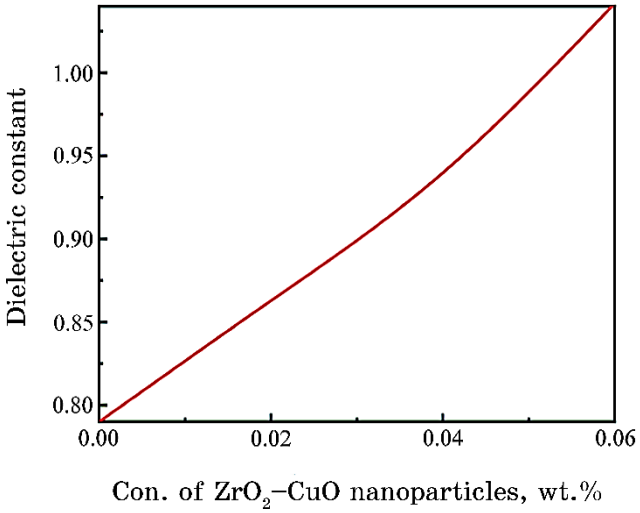

Fig. 3. Influence of ZrO_2–CuO NPs' contents on the ε′ of PVA–ZrO_2–CuO NCs at 100 Hz.

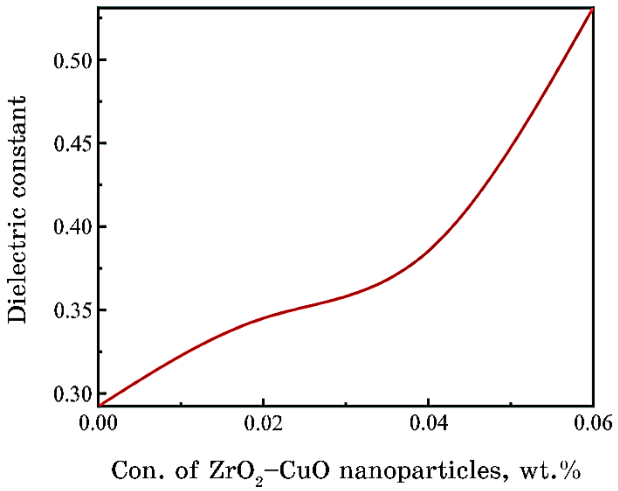

Fig. 4. Influence of ZrO_2–CuO NPs' contents on the ε″ of PVA–ZrO_2–CuO NCs at 100 Hz.

loss, respectively, for NCs consisting of PVA, ZrO_2, and CuO.

These figures illustrate the relationship between the concentrations of ZrO_2–CuO NPs and the corresponding increases in the values of ε′ and ε″. This observed trend can be attributed to interfacial polarisation within the NCs under an applied electric field [35, 36]. This polarisation increases the number of charge carriers, resulting

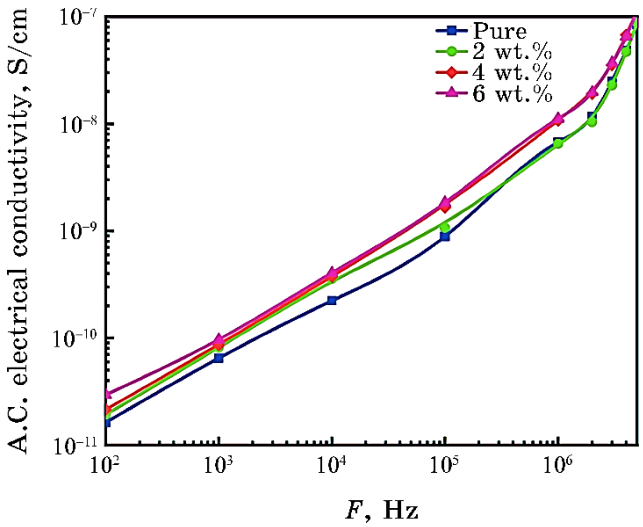

Fig. 5. Difference of conductivity for PVA–ZrO_2–CuO NCs with frequency *F*.

in higher values of the dielectric constant and dielectric loss. This behaviour aligns with the findings of other researchers [37, 38].

Figure 5 illustrates the relationship between A.C. electrical conductivity and frequency (*F*) for PVA–ZrO_2–CuO nanocomposites, specifically in terms of the A.C. electrical conductivity performance. The provided graph depicts a clear positive correlation between the A.C. electrical conductivity and the electric field frequency in all nanocomposite samples. The observed phenomena can be attributed to the migration of ions inside the clusters and the mobility of charge carriers [39, 40]. A higher charge concentration is observed at the interface between the electrode and the electrolyte at lower frequencies. As a result, there is a reduction in the mobility of ions, leading to a corresponding decline in electrical conductivity [41].

Figure 6 shows vibration of electrical conductivity with concentration of nanoparticles. The electrical conductivity demonstrates an upward trend with increased concentration of ZrO_2–CuO nanoparticles. The rise in electric charge can be attributed to the creation of saturated nanoparticles [42, 43]. Table shows values of ε', ε'' and $\sigma_{A.C.}$ for PVA–ZrO_2–CuO nanocomposites at 100 Hz.

4. CONCLUSION

The current study involves the fabrication of nanostructured films consisting of a composite material composed of polyvinyl alcohol

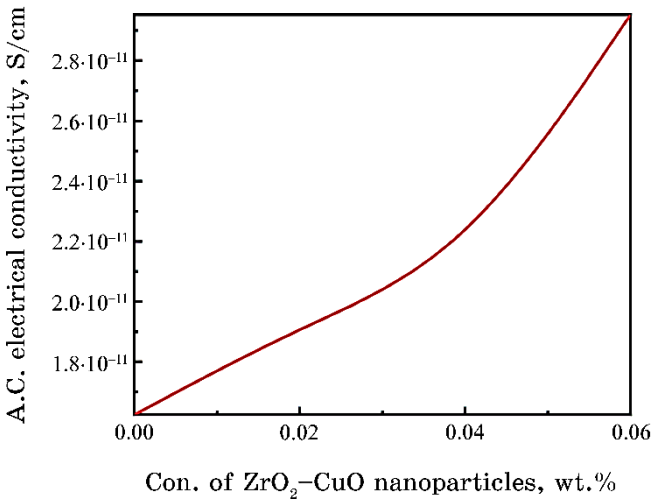

Fig. 6. Difference of electrical conductivity for PVA–ZrO_2–CuO NCs with of ZrO_2–CuO NPs' contents.

TABLE. Values of ε′, ε″ and $\sigma_{A.C.}$ for PVA–ZrO_2–CuO NCs at 100 Hz.

Contents of ZrO_2–CuO nanoparticles, wt.%	ε′	ε″	$\sigma_{A.C.}$, S/cm
0	0.79	0.29	$1.62 \cdot 10^{-11}$
2	0.86	0.34	$1.92 \cdot 10^{-11}$
4	0.93	0.38	$2.14 \cdot 10^{-11}$
6	1.04	0.53	$2.95 \cdot 10^{-11}$

(PVA), zirconium dioxide (ZrO_2), and copper oxide (CuO). These films were fabricated using the solution casting technique. The investigation focused on the electrical characteristics of nanostructures composed of PVA–ZrO_2–CuO. The investigation of the dielectric characteristics of nanocomposites consisting of PVA–ZrO_2–CuO revealed that the inclusion of ZrO_2–CuO nanoparticles led to an increase in the dielectric constant, dielectric loss, and A.C. electrical conductivity of the pristine PVA material. This enhancement was directly proportional to the concentration of ZrO_2–CuO nanoparticles in the nanocomposites.

Moreover, there was an increase in the dielectric constant from 0.79 to 1.04, as well as an increase in the dielectric loss from 0.29 to 0.53. As the electrical signal frequency escalates, a concomitant reduction in the dielectric constant and dielectric loss is observed, whilst the alternating current (A.C.) electrical conductivity exhibits an augmentation. The dielectric properties of the PVA–ZrO_2–CuO nanostructures demonstrate potential for utilization in various flex-

ible-nanoelectronics applications due to their cost-effectiveness, high energy-storage capacity, and minimal energy dissipation.

REFERENCES

1. Shuirong Li, Maoshuai Li, Chengxi Zhang, Shengping Wang, and Xinbin Ma, and Jinlong Gong, *International Journal of Hydrogen Energy*, **37**, No. 3: 2940 (2012); https://doi.org/10.1016/j.ijhydene.2011.01.009
2. A. H. Hadi and M. A. Habeeb, *Journal of Mechanical Engineering Research and Developments*, **44**, No. 3: 265 (2021); https://jmerd.net/03-2021-265-274
3. M. Ghanipour and D. Dorranian, *J. Nanomater.*, **2013**: 10 (2013); https://doi.org/10.1155/2013/897043
4. M. A. Habeeb and Z. S. Jaber, *East European Journal of Physics*, **4**: 176 (2022); doi:10.26565/2312-4334-2022-4-18
5. M. A. Habeeb, *European Journal of Scientific Research*, **57**, No. 3: 478 (2011).
6. Q. M. Jebur, A. Hashim, and M. A. Habeeb, *Egyptian Journal of Chemistry*, **63**: 719 (2020); https://dx.doi.org/10.21608/ejchem.2019.14847.1900
7. N. Tran, A. Mir, D. Mallik, A. Sinha, S. Nayar, and T. J. Webster, *Int. J. Nanomedicine,* **5**: 277 (2010).
8. S. M. Mahdi and M. A. Habeeb, *Optical and Quantum Electronics*, **54**, Iss. 12: 854 (2022); https://doi.org/10.1007/s11082-022-04267-6
9. N. Hayder, M. A. Habeeb, and A. Hashim, *Egyptian Journal of Chemistry*, **63**: 577 (2020); doi:10.21608/ejchem.2019.14646.1887
10. Shawna Nations, Monique Long, Mike Wages, Jonathan D. Maul, Christopher W. Theodorakis, and George P. Cobb Show, *Chemosphere*, **135**: 166 (2015); https://doi.org/10.1016/j.chemosphere.2015.03.078
11. M. A. Habeeb, A. Hashim, and N. Hayder, *Egyptian Journal of Chemistry*, **63**: 709 (2020); https://dx.doi.org/10.21608/ejchem.2019.13333.1832
12. A. Hashim, M. A. Habeeb, and Q. M. Jebur, *Egyptian Journal of Chemistry*, **63**: 735 (2020); https://dx.doi.org/10.21608/ejchem.2019.14849.1901
13. S. M. Mahdi and M. A. Habeeb, *Physics and Chemistry of Solid State*, **23**, No. 4: 785 (2022); doi:10.15330/pcss.23.4.785-792
14. Madalina Elena Grigore, Elena Ramona Biscu, Alina Maria Holban, Monica Cartelle Gestal, and Alexandru Mihai Grumezescu, *Pharmaceuticals*, **9**, No. 4: 75 (2016); https://doi.org/10.3390/ph9040075
15. M. A. Habeeb and W. S. Mahdi, *Int'l Journal of Emerging Trends in Engineering Research*, **7**, No. 9: 247 (2019); doi:10.30534/ijeter/2019/06792019
16. M. A. Habeeb and R. S. Abdul Hamza, *Journal of Bionanoscience*, **12**, No. 3: 328 (2018); https://doi.org/10.1166/jbns.2018.1535
17. Shruti Nambiar and John T. W. Yeow, *ACS Applied Materials & Interfaces*, **4**, No. 11: 5717 (2012); https://doi.org/10.1021/am300783d
18. M. A. Habeeb, A. Hashim, and N. Hayder, *Egyptian Journal of Chemistry*, **63**: 697 (2020); https://dx.doi.org/10.21608/ejchem.2019.12439.1774
19. M.A. Habeeb and W. K. Kadhim, *Journal of Engineering and Applied Sciences*, **9**, No. 4: 109 (2014); doi:10.36478/jeasci.2014.109.113
20. M. Hdidar, S. Chouikhi, A. Fattoum, M. Arous, and A. Kallel, *J. of Alloys and Compounds*, **750**: 375 (2018); https://doi.org/10.1016/j.jallcom.2018.03.272
21. M. A. Habeeb, *Journal of Engineering and Applied Sciences*, **9**, No. 4: 102 (2014); doi:10.36478/jeasci.2014.102.108

22. Hyeon Jeong Park, Arash Badakhsh, Ik Tae Im, Min-Soo Kim, and Chan Woo Park, *Applied Thermal Engineering*, **107**: 907 (2016); https://doi.org/10.1016/j.applthermaleng.2016.07.053
23. S. M. Mahdi and M. A. Habeeb, *Digest Journal of Nanomaterials and Biostructures*, **17**, No. 3: 941 (2022); https://doi.org/10.15251/DJNB.2022.173.941
24. G. A. Eid, A. Kany, M. El-Toony, I. Bashter, and F. Gaber, *Arab. J. Nucl. Sci. Appl.*, **46**, No. 2: 226 (2013).
25. Araa Hassan Hadi and Majeed Ali Habeeb, *Journal of Physics: Conference Series*, **1973:** 012063 (2021); doi:10.1088/1742-6596/1973/1/012063
26. Q. M. Jebur, A. Hashim, and M. A. Habeeb, *Egyptian Journal of Chemistry*, **63**, No. 2: 611 (2020); https://dx.doi.org/10.21608/ejchem.2019.10197.1669
27. B. H. Rabee and I. Oreibi, *Bulletin of Electrical Engineering and Informatics*, **7**, No. 4: 538 (2018); https://doi.org/10.11591/eei.v7i4.924
28. M. A. Habeeb and A. H. Mohammed, *Optical and Quantum Electronics*, **55**, Iss. 9: 791 (2023); https://doi.org/10.1007/s11082-023-05061-8
29. M. H. Dwech, M. A. Habeeb, and A. H. Mohammed, *Ukr. J. Phys.*, **67**, No. 10: 757 (2022); https://doi.org/10.15407/ujpe67.10.757
30. R. S. Abdul Hamza and M. A. Habeeb, *Optical and Quantum Electronics*, **55**, Iss. 8: 705 (2023); https://doi.org/10.1007/s11082-023-04995-3
31. Morget Martin, Neena Prasad, Muthu Mariappan Sivalingam, D. Sastikumar, and Balasubramanian Karthikeyan, *Journal of Material Science: Material in Electronics*, **29**: 365 (2018); doi:10.1007/s10854-017-7925-z
32. M. A. Habeeb and W. H. Rahdi, *Optical and Quantum Electronics*, **55**, Iss. 4: 334 (2023); https://doi.org/10.1007/s11082-023-04639-6
33. R. Dalven and R. Gill, *J. Appl. Phys.*, **38**, No. 2: 753 (1967); doi:10.1063/1.1709406
34. H. N. Chandrakala, B. Ramaraj, Shivakumaraiah, G. M. Madhu, and Siddaramaiah, *Journal of Alloys and Compounds*, **551**: 531 (2013); https://doi.org/10.1016/j.jallcom.2012.10.188
35. R. S. Abdul Hamza, M. A. Habeeb, *Optical and Quantum Electronics*, **55**, Iss. 8: 705 (2023); https://doi.org/10.1007/s11082-023-04995-3
36. Anjana Goswami, A. K. Bajpai, Jaya Bajpai, and B. K. Sinha, *Polym. Bull.*, **75**: 781 (2018); https://doi.org/10.1007/s00289-017-2067-2
37. S. M. Mahdi and M. A. Habeeb, *AIMS Materials Science*, **10**, No. 2: 288 (2023); doi:10.3934/matersci.2023015
38. O. E. Gouda, S. F. Mahmoud, A. A. El-Gendy, and A. S. Haiba, *Indonesian Journal of Electrical Engineering*, **12**, No. 12: 7987 (2014); https://doi.org/10.11591/telkomnika.v12i12.6675
39. M. A. Habeeb and R. S. A. Hamza, *Indonesian Journal of Electrical Engineering and Informatics*, **6**, No. 4: 428 (2018); doi:10.11591/ijeei.v6i1.511
40. N. K. Al-Sharifi and M. A. Habeeb, *East European Journal of Physics*, **2**: 341 (2023); doi:10.26565/2312-4334-2023-2-40
41. Y. T. Prabhu, K. Venkateswara Rao, B. Siva Kumari, Vemula Sesha Sai Kumar, and Tambur Pavani, *International Nano Letters*, **5**: 85 (2015); https://doi.org/10.1007/s40089-015-0141-z
42. Z. S. Jaber, M. A. Habeeb, and W. H. Radi, *East European Journal of Physics*, **2**: 228 (2023); doi:10.26565/2312-4334-2023-2-25
43. A. A. Mohammed and M. A. Habeeb, *East European Journal of Physics*, **2**: 157 (2023); doi:10.26565/2312-4334-2023-2-15