Наносистеми, наноматеріали, нанотехнології
Nanosistemi, Nanomateriali, Nanotehnologii
2024, т. 22, № 2, сс. 437–446
https://doi.org/10.15407/nnn.22.02.437

PACS numbers: 77.22.Ch, 77.22.Gm, 78.20.Ci, 78.67.Sc, 81.07.Pr, 82.35.Np, 85.35.Ds

Tailoring the A.C. Electrical Properties of TiO_2/Si_3N_4-NPs-Doped PVP to Use in Electrical and Electronics Applications

Ahmed Hashim and M. H. Abbas

College of Education for Pure Sciences,
Department of Physics,
University of Babylon,
Hillah, Iraq

This work aims to investigate the A.C. electrical properties of PVP/TiO_2/Si_3N_4 nanocomposites (PVP—polyvinyl pyrrolidine) to employ them in various electrical and electronic applications. The A.C. electrical properties of PVP/TiO_2/Si_3N_4 nanocomposites are measured in frequency range from 100 Hz to 5 MHz. The results show that the dielectric parameters such as dielectric constant, dielectric loss and electrical conductivity are increasing with an increase in TiO_2/Si_3N_4 concentration. The dielectric constant and dielectric loss of PVP/TiO_2/Si_3N_4 nanocomposites are reduced, while the electrical conductivity is increased, with increasing of the frequency. The obtained results indicate that the PVP/TiO_2/Si_3N_4 nanocomposites can be useful in different electrical and electronics fields.

Цю роботу спрямовано на дослідження електричних властивостей нанокомпозитів ПВП/TiO_2/Si_3N_4 (ПВП — полівінілпіролідин) на змінному струмі для використання їх у різних електричних та електронних застосуваннях. Електричні властивості на змінному струмі у нанокомпозитах ПВП/TiO_2/Si_3N_4 міряються в діяпазоні частот від 100 Гц до 5 МГц. Результати показують, що діелектричні параметри, такі як діелектрична проникність, діелектричні втрати й електропровідність, зростають зі збільшенням концентрації TiO_2/Si_3N_4. З підвищенням частоти діелектрична проникність і діелектричні втрати нанокомпозитів ПВП/TiO_2/Si_3N_4 зменшуються, а електропровідність збільшується. Одержані результати вказують на те, що нанокомпозити ПВП/TiO_2/Si_3N_4 можуть бути корисними в різних сферах електрики й електроніки.

Key words: nanocomposite, TiO_2/Si_3N_4, polymer, dielectric constant, conductivity.

Ключові слова: нанокомпозит, TiO_2/Si_3N_4, полімер, діелектрична проникність, електропровідність.

(Received 30 June, 2023; in revised form, 26 August, 2023)

1. INTRODUCTION

Modern electronics heighten the demand for adaptable, multipurpose, eco-friendly dielectric materials with superior properties. Historically, ceramics were used as dielectric materials; however, it possessed undesirable properties such as brittleness, processing difficulties, and low stability. Polymers have superior flexibility, processability, and lightweight, when compared to ceramics. In addition, they gained significant interest in science and technology during the last decade as a dielectric or interfacial layer between metals and semiconductors. Among the polymers, biodegradable, nontoxic, and hydrophilic ones have specific research interest, as they can be applicable in bioelectronics [1].

Flexible electronics are attracting increased attention in the electronic industry day by day due to their compact nature and ease of handling. Along with other electronics, flexible dielectric materials are also getting popular for many applications like in field effect transistors (FET), gate dielectrics, pulse power systems, sensors and energy storage devices, *etc*. Polymers are attractive to synthesize flexible materials, but they have limitations of low capacitance and low dielectric constants. In last few years, efforts have been made to enhance dielectric constant of polymers using by either dielectric or conducting fillers [2].

Silicon nitride (Si_3N_4) is a non-oxide ceramic material with a density of 3.4 g/cc, with high thermal conductivity 30 W/(m·K), low thermal expansion, and high compressive strength 4500 MPa. In addition, it has high-temperature stability, high fracture toughness, and high thermal shock resistance [3].

Nanocrystalline TiO_2 is a humongous semiconductor with many useful features, such as excellent photocatalytic activity and chemical and thermal stability. It is a low-cost and non-toxic semiconductor with unique properties, which allow insertion of it as nanoparticles (NPs) into polymeric matrices, and this is potential strategy for developing new nanocomposites with improved properties [4].

PVP is an amorphous and water-soluble polar polymer due to the existence of double bond in pyrrolidine ring, and hydroxyl groups existing in the structure [5].

The nanocomposites have nanostructure doped with various materials and are included in many applications in various approaches like radiation shielding and bioenvironmental [6–11], energy storage [12–14], electronics and optoelectronics [15–29], optical fields [30–39], sensors [40, 41], antibacterial [42–47].

The present works objects to investigate the dielectric properties of $PVP/TiO_2/Si_3N_4$ nanocomposites to employ in various electrical and electronics applications.

2. MATERIALS AND METHODS

Films of $PVP/TiO_2/Si_3N_4$ nanocomposites have been prepared from PVP as polymer matrix with TiO_2/Si_3N_4 NPs as filler. The nanocomposites films of $PVP/TiO_2/Si_3N_4$ nanomaterials were fabricated using casting technique. The films prepared with different concentrations: $C_1 = 12.5$ gm/L, $C_2 = 25$ gm/L, and $C_3 = 50$ gm/L and ratio of TiO_2/Si_3N_4 NPs (6%) provided with concentration of 50% TiO_2 and 50% Si_3N_4.

The dielectric properties of $PVP/TiO_2/Si_3N_4$ nanocomposites were examined at frequency (F) ranged from 100 Hz to 5 MHz using LCR meter (HIOKI 3532-50 LCR HI TESTER).

The dielectric constant (ε') is given by [48]:

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

wherever C_p is the capacitance of matter and C_0 is the vacuum capacitance.

Dielectric loss (ε'') is determined by [49]:

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

where D is the dispersion factor.

The A.C. electrical conductivity is obtained by [50]:

$$\sigma_{A.C.} = 2\pi F \varepsilon' D \varepsilon_0. \tag{3}$$

3. RESULTS AND DISCUSSION

Figures 1 and 2 show the variation of dielectric constant with frequency and concentration for $PVP/TiO_2/Si_3N_4$ nanocomposites, respectively.

Because the values of dielectric constant drop with increasing frequency, for the dipole, it is difficult to spin accurately and easily, and its oscillation begins to occur after this field. This is because the dielectric-constant values decrease.

In addition, there was no evidence of relaxation peaks, which points to a non-Debye response.

Figures 3 and 4 demonstrates the dielectric loss behaviours with frequency and concentration, respectively, which show that the mo-

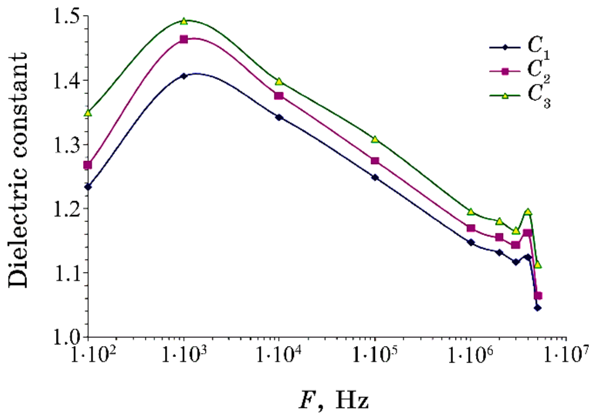

Fig. 1. Variation of dielectric constant for $PVP/TiO_2/Si_3N_4$ nanocomposites with frequency.

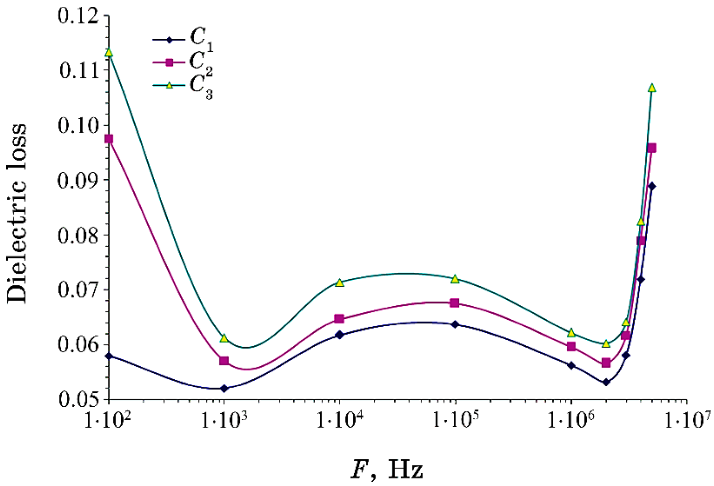

Fig. 2. Dielectric loss variation for $PVP/TiO_2/Si_3N_4$ nanocomposites with frequency.

tion of ions is recognized as the fundamental foundation of nanocomposite dielectric loss at lower frequencies, leading to a decrease in dielectric loss as a function of rising frequency.

Thus, the high value of the dielectric loss at low frequencies indicates the impact of ion jumping. The dielectric constant and dielectric loss are increased with increasing concentration that is attributed to rise in the number of charge carriers [51–63].

The performances of A.C. electrical conductivity of $PVP/TiO_2/Si_3N_4$ nanocomposites with frequency and concentration are represented in

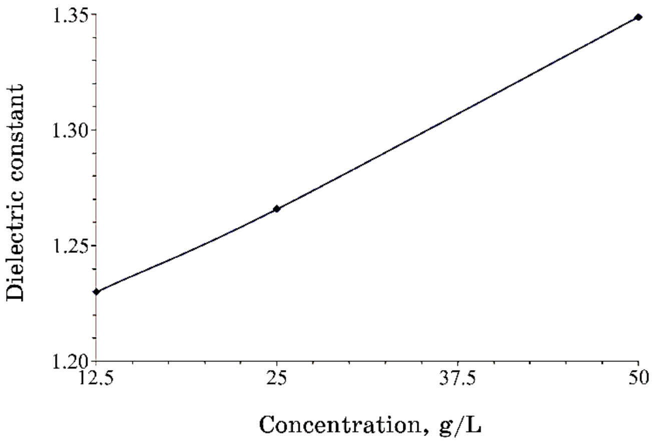

Fig. 3. Behaviour of dielectric constant for PVP/TiO_2/Si_3N_4 nanocomposites with concentration.

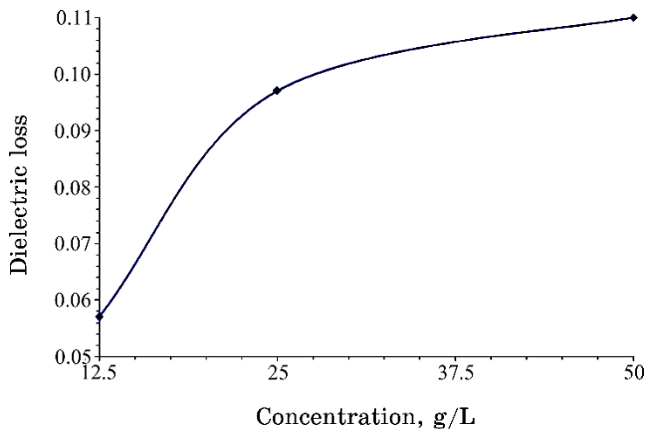

Fig. 4. Dielectric loss performance for PVP/TiO_2/Si_3N_4 nanocomposites with concentration.

Figs. 5 and 6, respectively.

The A.C. conductivity increases with the concentration.

In all films, conductivity increases with frequency. The bonds are designed to switch at higher frequencies, resulting in a dielectric transition with vulnerable trustworthy polar functional groups, which causes physiological adaptations within the polymer structure *via* the formation of charge transfer complexes, implying increased electrical conductivity of the films.

The rise of A.C. electrical conductivity with concentration can be due to increase of charge-carriers' number [64–70].

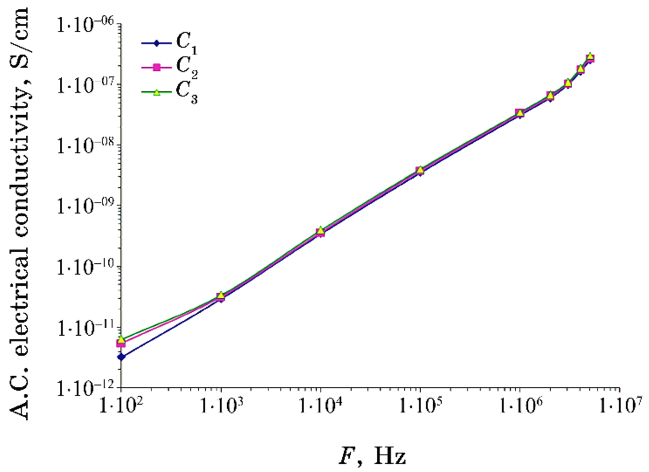

Fig. 5. Performance of A.C. electrical conductivity for $PVP/TiO_2/Si_3N_4$ nanocomposites with frequency.

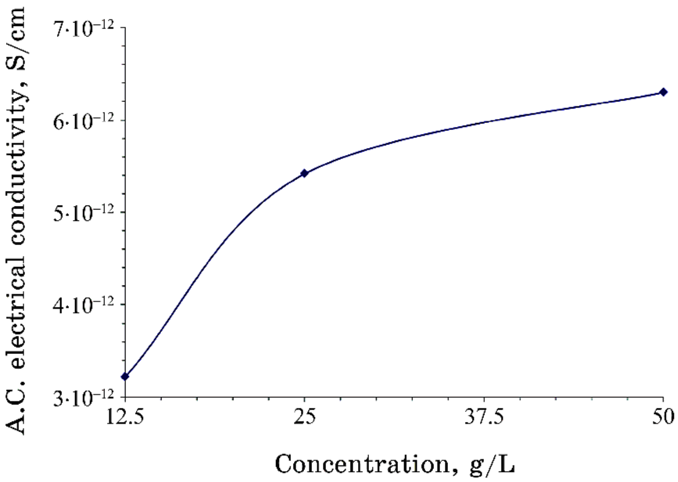

Fig. 6. Behaviour of A.C. electrical conductivity for $PVP/TiO_2/Si_3N_4$ nanocomposites with concentration.

4. CONCLUSIONS

The present study includes an investigation of A.C. electrical properties for $PVP/TiO_2/Si_3N_4$ nanocomposites to utilize them in different electrical and electronics fields. The A.C. electrical properties of $PVP/TiO_2/Si_3N_4$ nanocomposites were tested in frequency ranged of 100 Hz–5 MHz.

The results demonstrated that the dielectric constant, dielectric loss and electrical conductivity are increased with an increase in concentration. The dielectric constant and dielectric loss of $PVP/TiO_2/Si_3N_4$ nanocomposites are reduced, while the electrical conductivity is increased, with increasing of the frequency. The final results designated that the $PVP/TiO_2/Si_3N_4$ nanocomposites can be functional in many electrical and electronics applications.

REFERENCES

1. K. Parangusan, V. Subramaniam, A. B. Ganesan, P. S. Venkatesh, and D. Ponnamma, *J. Mater. Sci.: Mater. Electron*, **34**: 1110 (2023); https://doi.org/10.1007/s10854-023-10478-8
2. S. Ishaq, F. Kanwa, S. Atiq, M. Moussa, U. Azhar, and D. Losic, *Materials*, **13**: 1 (2020); doi:10.3390/ma13010205
3. M. B. Pasha, R. N. Rao, S. Ismail, and M. Gupta, *Appl. Sci.*, **12**: 1 (2022); https://doi.org/10.3390/app12126138
4. L. H. Gaabour, *AIP Advances*, **11**: 1 (2021); doi:10.1063/5.0062445
5. E. E. Herbei, M. Busila, P. Alexandru, S. Epure, and V. Musat, *Mater. Plast.*, **59**, No. 1: 1 (2022); https://doi.org/10.37358/MP.22.1.5554
6. A. Hashim and Z. S. Hamad, *Journal of Bionanoscience*, **12**, No. 4: 488 (2018); doi:10.1166/jbns.2018.1551
7. A. Hashim and Z. S. Hamad, *Journal of Bionanoscience*, **12**, No. 4: 504 (2018); doi:10.1166/jbns.2018.1561
8. B. Abbas and A. Hashim, *International Journal of Emerging Trends in Engineering Research*, **7**, No. 8: 131(2019); https://doi.org/10.30534/ijeter/2019/06782019
9. K. H. H. Al-Attiyah, A. Hashim, and S. F. Obaid, *Journal of Bionanoscience*, **12**: 200 (2018); doi:10.1166/jbns.2018.1526
10. H. A. J. Hussien, A. Hadi, and A. Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 4: 1001 (2022); https://doi.org/10.15407/nnn.20.04.1001
11. A. Hashim and N. Hamid, *Journal of Bionanoscience*, **12**, No. 6: 788 (2018); doi:10.1166/jbns.2018.1591
12. A. Hadi, A. Hashim, and D. Hassan, *Bulletin of Electrical Engineering and Informatics*, **9**, No. 1: 83 (2020); doi:10.11591/eei.v9i1.1323
13. H. Ahmed and A. Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 4: 951 (2022); https://doi.org/10.15407/nnn.20.04.951
14. A. S. Shareef, F. R. Lafta, A. Hadi, and A. Hashim, *International Journal of Scientific & Technology Research*, **8**, Iss. 11: 1041 (2019).
15. A. Hazim, A. Hashim, and H. M. Abduljalil, *Nanosistemi, Nanomateriali, Nanotehnologii*, **18**, Iss. 4: 983 (2020); https://doi.org/10.15407/nnn.18.04.983
16. A. Hashim and Z. S. Hamad, *Nanosistemi, Nanomateriali, Nanotehnologii*, **18**, Iss. 4: 969 (2020); https://doi.org/10.15407/nnn.18.04.969
17. G. Ahmed and A. Hashim, *Silicon*, **15**: 3977 (2023); https://doi.org/10.1007/s12633-023-02322-9
18. M. H. Meteab, A. Hashim, and B. H. Rabee, *Opt. Quant. Electron.*, **55**: 187

(2023); https://doi.org/10.1007/s11082-022-04447-4
19. B. Mohammed, H. Ahmed, and A. Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **21**, Iss. 1: 113 (2023); https://doi.org/10.15407/nnn.21.01.113
20. A. Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **19**, Iss. 3: 647 (2021); https://doi.org/10.15407/nnn.19.03.647
21. A. Hazim, A. Hashim, and H. M. Abduljalil, *Egypt. J. Chem.*, **64**, No. 1: 359 (2021); doi:10.21608/EJCHEM.2019.18513.2144
22. H. Ahmed and A. Hashim, *Journal of Molecular Modeling*, **26**: 1 (2020); doi:10.1007/s00894-020-04479-1
23. H. Ahmed and A. Hashim, *Silicon*, **14**: 4907 (2022); https://doi.org/10.1007/s12633-021-01258-2
24. A. Hashim, *Opt. Quant. Electron.*, **53**: 1 (2021); https://doi.org/10.1007/s11082-021-03100-w
25. H. Ahmed and A. Hashim, *Trans. Electr. Electron. Mater.*, **23**: 237 (2022); https://doi.org/10.1007/s42341-021-00340-1
26. H. Ahmed and A. Hashim, *Silicon*, **14**: 7025 (2021); https://doi.org/10.1007/s12633-021-01465-x
27. A. Hazim, A. Hashim, and H. M. Abduljalil, *Trans. Electr. Electron. Mater.*, **21**: 48 (2019); https://doi.org/10.1007/s42341-019-00148-0
28. A. F. Kadhim and A. Hashim, *Opt. Quant. Electron.*, **55**: 432 (2023); https://doi.org/10.1007/s11082-023-04699-8
29. H. Ahmed and A. Hashim, *Opt. Quant. Electron.*, **55**: 280 (2023); https://doi.org/10.1007/s11082-022-04528-4
30. N. A. H. Al-Aaraji, A. Hashim, A. Hadi, and H. M. Abduljalil, *Silicon*, **14**: 10037 (2022); https://doi.org/10.1007/s12633-022-01730-7
31. H. Ahmed and A. Hashim, *Opt. Quant. Electron.*, **55**: 1 (2023); https://doi.org/10.1007/s11082-022-04273-8
32. W.O. Obaid and A. Hashim, *Silicon*, **14**: 11199 (2022); https://doi.org/10.1007/s12633-022-01854-w
33. O. B. Fadil and A. Hashim, *Silicon*, **14**: 9845 (2022); https://doi.org/10.1007/s12633-022-01728-1
34. H. Ahmed and A. Hashim, *Silicon*, **15**: 2339 (2023); https://doi.org/10.1007/s12633-022-02173-w
35. H. B. Hassan, H. M. Abduljalil, and A. Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 4: 941 (2022); https://doi.org/10.15407/nnn.20.04.941
36. H. A. Jawad and A. Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 4: 963 (2022); https://doi.org/10.15407/nnn.20.04.963
37. H. Ahmed and A. Hashim, *Silicon*, **14**: 6637 (2022); https://doi.org/10.1007/s12633-021-01449-x
38. H. Ahmed and A. Hashim, *Silicon*, **13**: 4331 (2020); https://doi.org/10.1007/s12633-020-00723-8
39. H. Ahmed and A. Hashim, *Transactions on Electrical and Electronic Materials*, **22**: 335 (2021); https://doi.org/10.1007/s42341-020-00244-6
40. H. Ahmed and A. Hashim, *International Journal of Scientific & Technology Research*, **8**, Iss. 11: 1014 (2019).
41. B. Mohammed, H. Ahmed, A. Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 1: 187 (2022); https://doi.org/10.15407/nnn.20.01.187

42. O. B. Fadil and A. Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 4: 1029 (2022); https://doi.org/10.15407/nnn.20.04.1029
43. W. O. Obaid and A. Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 4: 1009 (2022); https://doi.org/10.15407/nnn.20.04.1009
44. M. H. Meteab, A. Hashim, and B. H. Rabee, *Nanosistemi, Nanomateriali, Nanotehnologii*, **21**, Iss. 1: 199 (2023); https://doi.org/10.15407/nnn.21.01.199
45. A. Hashim, I. R. Agool, and K. J. Kadhim, *Journal of Bionanoscience*, **12**, No. 5: 608 (2018); doi:10.1166/jbns.2018.1580
46. A. Hazim, A. Hashim, and H. M. Abduljalil, *International Journal of Emerging Trends in Engineering Research*, **7**, No. 8: 68 (2019); https://doi.org/10.30534/ijeter/2019/01782019
47. A. Hazim, H. M. Abduljalil, and A. Hashim, *International Journal of Emerging Trends in Engineering Research*, **7**, No. 8: 104 (2019); https://doi.org/10.30534/ijeter/2019/04782019
48. A. H. Selçuk, E. Orhan, S. Bilge Ocak, A. B. Selçuk, and U. Gökmen, *Materials Science–Poland*, **35**, Iss. 4: 885 (2017); doi:10.1515/msp-2017-0108
49. H. Shivashankar, K. A. Mathias, P. R. Sondar, M. H. Shrishail, and S. M. Kulkarni, *J. Mater. Sci.: Mater. Electron.*, **32**: 28674 (2021); https://doi.org/10.1007/s10854-021-07242-1
50. C. S. Rani and N. J. John, *Int. J. of Innovative Techno. and Exploring Eng.*, **8**, Iss. 11: 1285 (2019); https://doi.org/10.35940/ijitee.J9502.0981119
51. A. Hashim, A. Hadi, N. AH. Al-Aaraji, and F. L. Rashid, *Silicon*, **15**: 5725 (2023); https://doi.org/10.1007/s12633-023-02471-x
52. A.F. Kadhim and A. Hashim, *Silicon*, **15**: 4613 (2023); https://doi.org/10.1007/s12633-023-02381-y
53. H. A. Jawad and A. Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **21**, Iss. 1: 133 (2023); https://doi.org/10.15407/nnn.21.01.133
54. D. Hassan and A. Hashim, *Bulletin of Electrical Engineering and Informatics*, **7**, Iss. 4: 547 (2018); doi:10.11591/eei.v7i4.969
55. A. Hashim, M. H. Abbas, N. AH. Al-Aaraji, and A. Hadi, *J. Inorg. Organomet. Polym.*, **33**: 1 (2023); https://doi.org/10.1007/s10904-022-02485-9
56. A. Hashim, M. H. Abbas, N. AH. Al-Aaraji, and A. Hadi, *Silicon*, **15**: 1283 (2023); https://doi.org/10.1007/s12633-022-02104-9
57. M. H. Meteab, A. Hashim, and B. H. Rabee, *Silicon*, **15**: 1609 (2023); https://doi.org/10.1007/s12633-022-02114-7
58. N. Al-Huda Al-Aaraji, A. Hashim, A. Hadi, and H. M. Abduljalil, *Silicon*, **14**: 4699 (2022); https://doi.org/10.1007/s12633-021-01265-3
59. M. H. Meteab, A. Hashim, and B. H. Rabee, *Silicon*, **15**: 251 (2023); https://doi.org/10.1007/s12633-022-02020-y
60. A. Hashim, A. Hadi, and M. H. Abbas, *Opt. Quant. Electron.*, **55**: 642 (2023); https://doi.org/10.1007/s11082-023-04929-z
61. A. Hashim, A. Hadi, and M. H. Abbas, *Silicon*, **15**: 6431 (2023); https://doi.org/10.1007/s12633-023-02529-w
62. H. A. J. Hussien and A. Hashim, *J. Inorg. Organomet. Polym.*, **33**: 2331 (2023); https://doi.org/10.1007/s10904-023-02688-8
63. A. B. G. Trabelsi, A. M. Mostafa, F. H. Alkallas, W. B. Elsharkawy, A. N. Al-Ahmadi, H. A. Ahmed, S. S. Nafee, R. A. Pashameah, and E. A. Mwafy, *Micromachines*, **14**: 1 (2023);

https://doi.org/10.3390/mi14061195
64. A. Hashim and A. Jassim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 1: 177 (2022); https://doi.org/10.15407/nnn.20.01.177
65. A. Hashim and Z. S. Hamad, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 2: 507 (2022); https://doi.org/10.15407/nnn.20.02.507
66. B. Mohammed, H. Ahmed, and A. Hashim, *Journal of Physics: Conference Series*, **1879**: 1 (2021); doi:10.1088/1742-6596/1879/3/032110
67. D. Hassan and A. H. Ah-Yasari, *Bulletin of Electrical Engineering and Informatics*, **8**, Iss. 1: 52 (2019); doi:10.11591/eei.v8i1.1019
68. Z. S. Hamad and A. Hashim, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 1: 159 (2022); https://doi.org/10.15407/nnn.20.01.159
69. A. Hashim and Z. S. Hamad, *Nanosistemi, Nanomateriali, Nanotehnologii*, **20**, Iss. 1: 165 (2022); https://doi.org/10.15407/nnn.20.01.165
70. K. Parangusan, V. Subramaniam, A. B. Ganesan, P. S. Venkatesh, and D. Ponnamma, *J. Mater. Sci.: Mater. Electron.*, **34**: 1 (2023); https://doi.org/10.1007/s10854-023-10478-8