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Influence of CuO–SiO$_2$-Nanoparticles' Addition on Dielectric Characteristics of PVA for Nanodielectric Applications

Rehab Shather Abdul Hamza[1], Majeed Ali Habeeb[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), copper oxide (CuO), and silicon dioxide (SiO_2) are produced using the solution cast method. The samples are consisted of PVA serving as the organic host matrix, together with different amounts of nanosize CuO and SiO_2 ranging from 0 to 6 wt.%. This study investigates the electrical properties of nanocomposites (NCs), namely, PVA–CuO–SiO_2. An inquiry is carried out to examine the electrical properties of NCs throughout the frequency range of 100 to $5\cdot10^6$ Hz under standard temperature settings. The experimental findings indicate the reduction in the dielectric constant (ε') and loss (ε'') of the PVA–CuO–SiO_2 NCs with increasing frequency. The electrical conductivity $\sigma_{A.C.}$ of an alternating current (A.C.) increases with higher frequencies. The ε', ε'', and $\sigma_{A.C.}$ of pure PVA increase with the increasing concentration of the CuO–SiO_2 nanoparticles (NPs). The definitive results demonstrated that the PVA–CuO–SiO_2 nanostructures have promising potential for various electrical and electronic nanodevices.

Нанокомпозити, що складаються з полівінілового спирту (ПВС), оксиду Купруму (CuO) та діоксиду Силіцію (SiO_2), було одержано методом лиття з розчину. Зразки складалися з ПВС, який служив органічною матрицею-хазяїном, разом із різною кількістю нанорозмірних CuO та SiO_2 від 0 до 6 ваг.%. У цьому дослідженні вивчено електричні властивості нанокомпозитів (НК), а саме, ПВС–CuO–SiO_2. Було проведено дослідження з метою вивчення електричних властивостей НК у всьому діапазоні частот від 100 до $5\cdot10^6$ Гц за стандартних температурних умов. Експериментальні результати показали пониження діелектричної проникности (ε') та втрат (ε'') НК ПВС–CuO–SiO_2 зі збільшенням частоти. Електропровідність $\sigma_{A.C.}$ змінного струму збільшується за вищих частот. Значення ε′, ε″ і $\sigma_{A.C.}$ чистого ПВС збільшуються зі збільшенням концентрації наночастинок $CuO–SiO_2$. Остаточні результати продемонстрували, що наноструктури ПВС–$CuO–SiO_2$ мають багатообіцяючий потенціял для різних електричних та електронних нанопристроїв.

Key words: nanocomposites, PVA, $CuO–SiO_2$ nanoparticles, electrical properties.

Ключові слова: нанокомпозити, полівініловий спирт, наночастинки $CuO–SiO_2$, електричні властивості.

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1. INTRODUCTION

Nanotechnology is a recently emerged scientific field that explores the distinct characteristics of materials at the nanoscale scale, which vary dramatically from those shown by the same materials at higher particle sizes [1, 2]. It has revolutionized multiple domains, with medicine being the most significant beneficiary. Notably, nanotechnology relies on principles of biology, pharmacy, engineering, physics, and chemistry. Therefore, researchers must possess a comprehensive foundation encompassing all these disciplines. Nanotechnology has revolutionized several aspects of our lives. Examining the management of several illnesses has instilled significant optimism for the potential remedy of various formerly untreatable conditions. Nanotechnology has great potential for revolutionizing medical practices by enabling precise diagnostics and highly efficient treatments for life-threatening illnesses like cancer. These advancements will be realized over the next decade via nanomedicine [3, 4].

Polymer nanocomposites (NCs) have gained substantial attention from both academia and industry in recent decades and have emerged as essential materials for developing cutting-edge applications, particularly in the field of electrical engineering [5, 6]. Polyvinyl alcohol (PVA) is well recognized as a very important polymer and is extensively used in several crucial applications and industries. Examples of these applications and businesses include electrochromics, fuel cells, biomedical domains, and sensors. Polyvinyl alcohol (PVA) has distinct characteristics compared to other polymers, such as exceptional mechanical robustness, resistance to corrosion, and favourable thermal stability [7, 8].

Polyvinyl alcohol (PVA) is a hydrophilic artificial polymer that is a granular powder with no smell, transparent appearance, lack of taste, and white or cream hue. Due to its water-solubility, PVA may produce hydroxyl organic components. Two prominent features of

PVA are its susceptibility to biological degradation and its biocompatibility. Polyvinyl alcohol (PVA) has exceptional tensile strength and durability, along with a remarkable ability to resist the permeation of oxygen and odours. The visual propagation of light is exceptional. Additionally, it has exceptional attributes in terms of form, mixing, and adherence [9, 10].

Silicon dioxide, also known as silica, is a compound consisting of silicon and oxygen. Its chemical formula is SiO_2, and it is mostly found in nature as quartz. All types of silica have the same chemical makeup but vary in atomic arrangement [11, 12].

The SiO_2 particles operate as a solid plasticizer, enhancing the composite polymer dimensional stability and chemical and mechanical properties [13]. Moreover, SiO_2 is an amorphous, non-toxic material with several potential applications. Silica is a solid substance that lacks odour and comprises silicon (Si) and oxygen atoms (O_2). Silica (SiO_2) particles go airborne and aggregate to create non-combustible particulate matter [14, 15].

CuO nanoparticles (NPs) have been utilized to improve the characteristics of polymer films, regardless of whether they are derived from petroleum or biological sources. This is attributed to their ability to enhance the mechanical properties of polymers, relatively low toxicity, thermal stability, and high surface area to volume ratio [16]. Copper oxide is a metallic substance with semiconductor properties and unique optical, electrical, and magnetic attributes. It has found applications in several domains, such as near-infrared filters, sensors, catalysis, producing supercapacitors, magnetic storage media, and semiconductors [17, 18].

The electrical properties of pure PVA were improved by including the copper oxide (CuO) and silicon dioxide (SiO_2) nanoparticles (NPs) in this work. The study results show a substantial improvement in the aspects mentioned above.

2. MATERIALS AND METHODS

The casting approach was used to manufacture nanocomposite films by adding polyvinyl alcohol (PVA), copper oxide (CuO), and silicon dioxide (SiO_2) nanoparticles. The experimental protocol included the dissolution of pure polyvinyl alcohol (PVA) in 40 ml of distilled water for 45 minutes. A magnetic stirrer was used to agitate the mixture at 50°C, enhancing the solution uniformity and homogeneity throughout this procedure. The polymer was modified by adding copper oxide (CuO) and silicon dioxide (SiO_2) nanoparticles at varying weight percentages 0%, 2%, 4%, and 6%. Following four days of air-drying the solution at room temperature, the outcome was the achievement of polymer nanocomposite formation. The PVA–

CuO–SiO_2 NCs were obtained from the Petri dish and used for measurement. The dielectric properties of NCs were assessed using the LCR meter/HIOKI/3532/50/LCR-HI-TESTER with a frequency range from 100 Hz to 5 MHz.

To get the value of the dielectric constant (ε'), the following formula might be used [19, 20]:

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

where C_p, C_0 are signifying capacitance and vacuum capacitor.

Dielectric loss (ε'') is given by [21, 22]:

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

here, the displacement (D) is used.

The A.C. electrical conductivity is calculated as follows [23, 24]:

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

where ω is angular frequency.

3. RESULTS AND DISCUSSION

Figure 1 illustrates the variations in the dielectric properties of nanocomposites made up of polyvinyl alcohol (PVA), copper oxide (CuO), and silicon dioxide (SiO_2), referred to as PVA–CuO–SiO_2 nanocomposites, as a function of frequency. The results suggest that the ε' negatively correlates with the frequency (f) in all samples. At low frequencies, the insulating materials' dipoles align with the applied electric field, causing charge accumulation. This accumulation leads to increased polarization and, consequently, an increase in the ε'. At higher frequencies, the dipoles cannot align quickly enough with the direction of the applied electric field; this results in a reduction in polarization and, therefore, a drop in the ε' value. This characteristic has many applications, including communication antennas and microwave components [25, 26].

Figure 2 depicts the dielectric loss of nanocomposites made up of polyvinyl alcohol (PVA), copper oxide (CuO), and silicon dioxide (SiO_2), which varies with frequency. The graph data demonstrates a negative correlation between frequency and dielectric loss, indicating that as frequency increases, dielectric loss decreases. This behaviour is attributed to mobile charges inside the polymer backbone. The occurrence arises from diminishing the impact of space charge polarization as the frequency increases. The dielectric loss of PVA–CuO–SiO_2 NCs increases with more electrons, especially, at

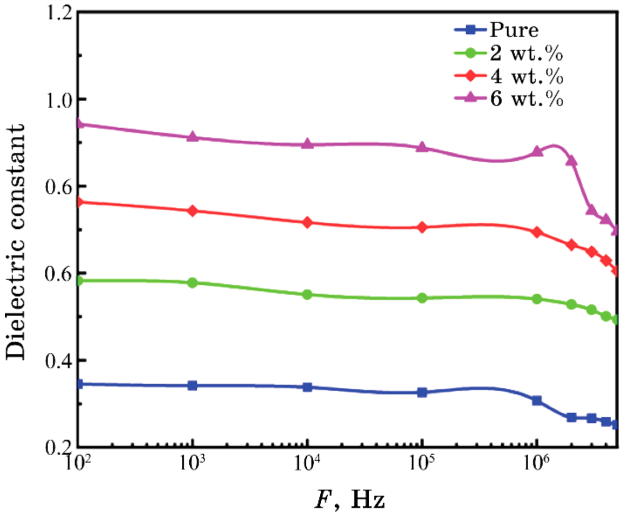

Fig. 1. Behaviour of ε′ with a frequency for the PVA–CuO–SiO$_2$ NCs.

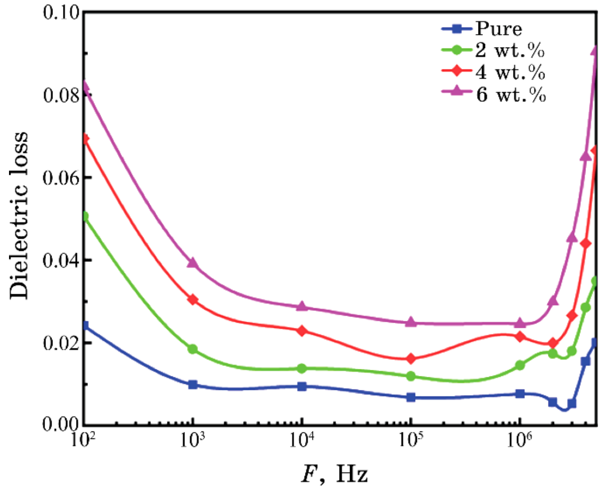

Fig. 2. Behaviour of ε″ with a frequency for the PVA–CuO–SiO$_2$ NCs.

intermediate frequencies, but decreases as the frequency increases [27–30].

Figures 3 and 4 depict the relationship between the levels of nanoparticles and the dielectric properties, including the dielectric constant and dielectric loss, in nanocomposites made of polyvinyl alcohol (PVA), copper oxide (CuO), and silicon dioxide (SiO_2).

The data demonstrates the relationship between the concentration of CuO–SiO$_2$ nanoparticles and the simultaneous rise in ε′ and ε″.

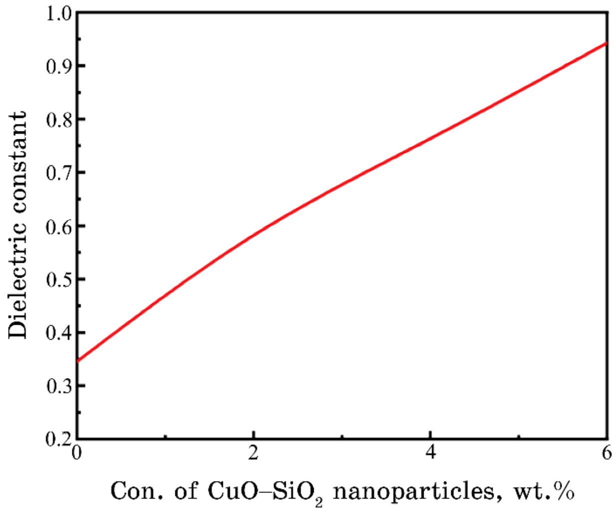

Fig. 3. Influence of $CuO-SiO_2$ NPs' content on the ε' of $PVA-CuO-SiO_2$ NCs at 100 Hz.

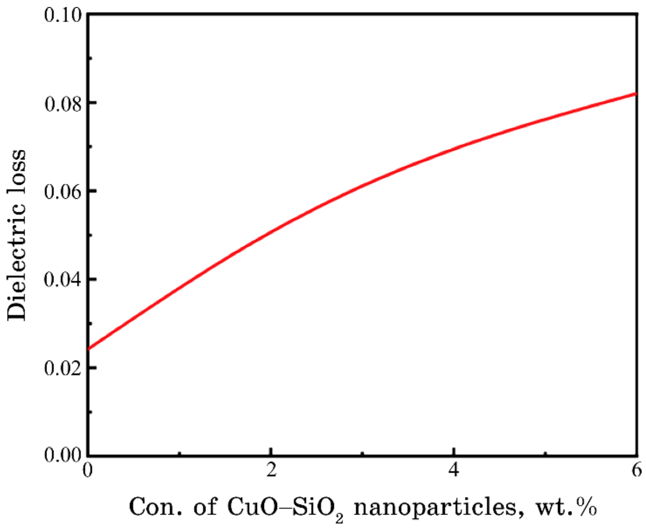

Fig. 4. Influence of $CuO-SiO_2$ NPs' content on the ε'' of $PVA-CuO-SiO_2$ NCs at 100 Hz.

The observed phenomena may be explained by interfacial polarization inside the nanocomposites when an electric field is applied [31, 32]. This polarization increases charge carriers, resulting in a higher dielectric constant and dielectric loss. This behaviour is consistent with the discoveries made by other researchers [33–36].

Figures 5 and 6 depict the correlation between the frequency (f) and the concentration of $CuO–SiO_2$ nanoparticles in the PVA–CuO–SiO_2 nanocomposites, especially, in connection to the performance of A.C. electrical conductivity. The graph demonstrates a direct relationship between the A.C. electrical conductivity and the electric

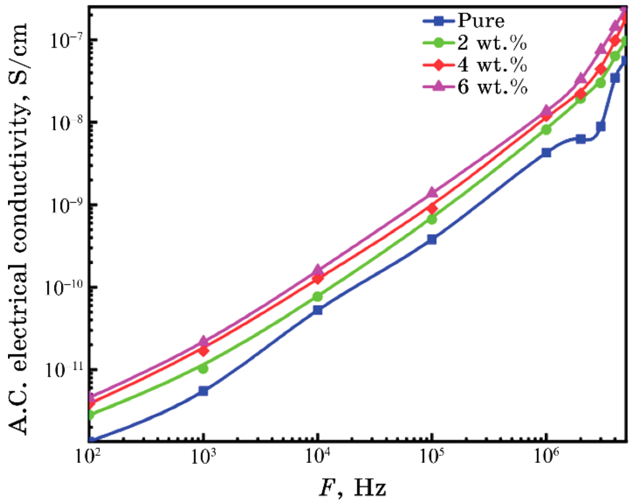

Fig. 5. Variation of conductivity for PVA–CuO–SiO_2 NCs with frequency f.

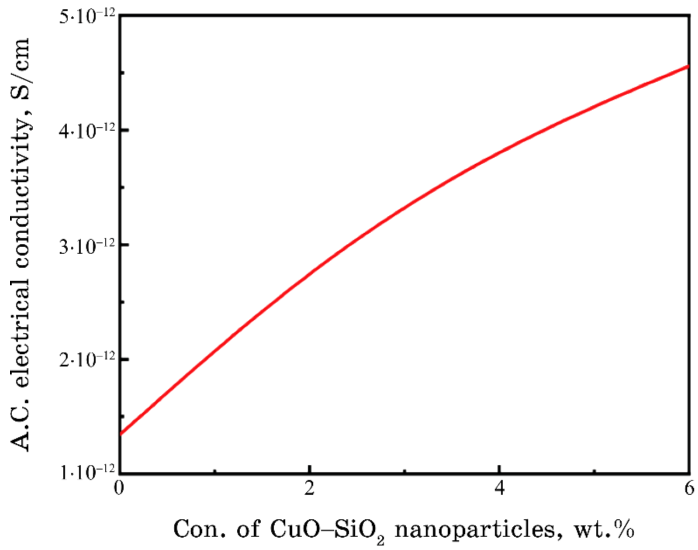

Fig. 6. Variation of electrical conductivity for PVA–CuO–SiO_2 NCs with $CuO–SiO_2$ NPs' contents.

TABLE. Dielectric constant, dielectric loss, and A.C. electrical conductivity values at 100 Hz for PVA–CuO–SiO_2 nanocomposites.

Content of CuO–SiO_2 NPs, wt.%	Dielectric constant	Dielectric loss	A.C. electrical conductivity, S/cm
0	0.34	0.024	$1.34\cdot10^{-12}$
2	0.58	0.050	$2.81\cdot10^{-12}$
4	0.76	0.069	$3.86\cdot10^{-12}$
6	0.94	0.082	$4.55\cdot10^{-12}$

field frequency in all nanocomposite samples. This phenomenon may be ascribed to the migration of ions inside the clusters and the movement of electrically charged particles [37–39]. At lower frequencies, there is a higher accumulation of charge at the interface between the electrode and electrolyte, leading to a decrease in the number of ions that can move and, therefore, a drop in electrical conductivity. The conductivity increases directly to the concentration of CuO–SiO_2 nanoparticles. The rise in electric charge results from the creation of fully saturated nanoparticles.

Table displays the dielectric constant, dielectric loss, and A.C. electrical conductivity values of PVA–CuO–SiO_2 nanocomposites at a frequency of 100 Hz [40–42].

4. CONCLUSION

The present investigation entails the fabrication of nanostructured films comprising PVA–CuO–SiO_2 by the solution casting technique. An inquiry has been carried out to examine the electrical properties of nanostructures consisting of PVA–CuO–SiO_2. The dielectric properties of PVA–CuO–SiO_2 nanocomposites indicate that ε', ε'', and $\sigma_{A.C.}$ of pure PVA increase, when the concentration of CuO–SiO_2 nanoparticles increases. In addition, the ε' increased from 0.34 to 0.94 at a frequency of 100 Hz, whereas the ε'' increased from 0.024 to 0.082 at the same frequency. The ε' and ε'' drop in magnitude as the frequency increases, but the A.C. electrical conductivity experiences an increase. The dielectric properties of the PVA–CuO–SiO_2 nanostructures render them highly appropriate for a wide range of flexible nanoelectronics applications, owing to their cost-effectiveness, high energy-storage capacity, and low loss.

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