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Novel Pressure Sensors Prepared from PVA–CMC–TiC Nanocomposites: Fabrication and Characterization

Ahmed Hashim and Qassim Hadi

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

In this paper, preparation of new pressure sensors with low cost and lightweight, and their structural and dielectric properties are investigated. The pressure sensors are prepared from polyvinyl alcohol (PVA; 50 wt.%) and carboxyl methylcellulose (CMC; 50 wt.%) with different concentrations (1, 2 and 3 wt.%) of titanium-carbide nanoparticles. The dielectric properties are measured in the frequency range from 100 Hz to 5 MHz. The experimental results show that the dielectric constant and dielectric loss of PVA–CMC–TiC nanocomposites are decreased with increase in frequency of applied electric field. The A.C. electrical conductivity increases with increasing the frequency. The dielectric constant, dielectric loss, and A.C. electrical conductivity of PVA–CMC blend are increased with increase of concentration of TiC nanoparticles. The results of pressure sensor application show that the electrical resistance of PVA–CMC–TiC nanocomposites decreases with increase in pressure.

У цій роботі досліджено приготування нових датчиків тиску з низькою вартістю та невеликою вагою, а також їхні структурні та діелектричні властивості. Датчики тиску готуються з полівінілового спирту (ПВС; 50 ваг.%) і карбоксильної метилцелюлози (КМЦ; 50 ваг.%) з різною концентрацією (1, 2 і 3 ваг.%) наночастинок карбиду Титану. Діелектричні властивості вимірюються в діапазоні частот від 100 Гц до 5 МГц. Експериментальні результати показують, що діелектрична проникність і діелектричні втрати нанокомпозитів ПВС–КМЦ–TiC зменшуються зі збільшенням частоти прикладеного електричного поля. Електропровідність змінного струму збільшується зі збільшенням частоти. Діелектрична проникність, діелектричні втрати й електропровідність змінного струму суміші ПВС–КМЦ збільшуються зі збільшенням концентрації наночастинок TiC. Результати застосування датчика тиску показують, що електричний опір нанокомпозитів ПВС–КМЦ–TiC понижується зі збільшенням тиску.

Key words: nanocomposite, titanium carbide, conductivity, pressure sensor.

Ключові слова: наноккомпозит, карбід Титану, провідність, датчик тиску.

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1. INTRODUCTION

Recently there has been a constant search for new materials that possess high dielectric permittivity and good mechanical properties for important technological applications. Polymers are materials with low-density flexible, easy to fabricate and superior in dielectric breakdown strength and mechanically more compliant than the ceramics, but its dielectric values are much lower than those of the ceramics [1].

The addition of inorganic nanoparticles to polymers allows the modification of the polymer physical properties as well as the implementation of new features in the polymer matrix. With decreasing particle size, the ratio of surface/volume increases, so that surface properties become crucial. Smaller the particles are, more important will be the surface properties, thereby influencing interfacial properties, agglomeration behaviour, and the physical properties of the particles. The intensity of these properties changes depending upon the nature, composition, concentration and size of the nanoparticles [2].

Addition of small amount of nanomaterial could improve the performance of polymeric materials due to their small size, large specific surface area, quantum confinement effects, and strong interfacial interactions. Among these polymers, polyvinyl alcohol (PVA) is a polymer that has been studied intensively due to its good film forming and physical properties, high hydrophilicity, processability, biocompatibility, and good chemical resistance. Polyvinyl alcohol is a good insulating material with low conductivity; hence, it is very useful in microelectronic industry. Its electrical conductivity depends on the thermally generated carriers and the addition of suitable dopants. Moreover, the PVA polymer extends the industrial applications in optical, pharmaceutical, medical, and membrane fields. PVA is a semi-crystalline material with several interesting physical properties, which are very useful in technical applications [1, 3]. Polymer nanocomposites containing semiconductor nanoparticles are shown to be significant for building electronic and optoelectronic devices, such as solar cells, light-emitting diodes, optical limiters, and various types of sensors [4–6].

Many of the modern technologies require materials with unusual combinations of properties that cannot be met by conventional met-

al alloys, ceramics and polymers. Nanocomposite development provides for new technologies and business opportunities in many sectors of aerospace, automobile, electronics and biotechnology industries.

Titanium carbide (TiC) is widely used as a reinforcing particle to produce metal matrix composites due to its hardness, chemical inertia, high melting point and stability. Composites comprising titanium carbide metal matrix can be characterized by a good wear resistance with a relatively low coefficient of friction [7].

2. EXPERIMENTAL PART

The nanocomposites of PVA-CMC-TiC were prepared by dissolving 1 gm of PVA-CMC blend in 20 ml of distilled water with concentration: 50 wt.% PVA and 50 wt.% CMC by using magnetic stirrer to mix the polymers for 1 hour to obtain solution that is more homogeneous. The TiC nanoparticles were added to polymers' mixture with different concentrations (1, 2 and 3 wt.%). The casting method is used to prepare the samples of PVA-CMC-TiC nanocomposites in the template (Petri dish has diameter of 10 cm). The samples were prepared with thickness range 117–140 μm .

The dielectric properties of PVA-CMC-TiC nanocomposite samples are studied with frequency range from 100 Hz to $5 \cdot 10^6$ Hz by using LCR meter type (HIOKI 3532-50 LCR HI TESTER). The pressure sensor of samples is investigated by measuring the resistance between two electrodes on the top and bottom of the sample for different pressures' range 80–200 bar.

The dielectric constant, ε' , of nanocomposites is defined by using the following equation [8]:

$$\varepsilon' = \frac{C_p}{C_o}, \quad (1)$$

where C_p is parallel capacitance and C_o is vacuum capacitor.

The dielectric loss, ε'' , of nanocomposites is written by following equation [8]:

$$\varepsilon'' = \varepsilon' D, \quad (2)$$

where D is dispersion factor.

The A.C. electrical conductivity is defined by following equation [9]:

$$\sigma_{\text{A.C.}} = w\varepsilon''\varepsilon_o, \quad (3)$$

where w is the angular frequency.

3. RESULTS AND DISCUSSION

The FT-IR spectra for pure polymer blend and PVA-CMC-TiC nanocomposite films are shown in Fig. 1. In the spectra of nanocomposites, the broad and strong band centred at 3366 cm^{-1} is assigned to the stretching vibration of hydroxyl group OH. The band observed at 1601 cm^{-1} is assigned to the stretching vibrational band of C=O. The two bands observed at 1416 and 1356 cm^{-1} are assigned as CH_3 bending vibration and CH_2 stretching, respectively. The band at 1056 cm^{-1} arises from the C-O stretching vibration, while the band at 917 cm^{-1} results from CH_2 rocking vibration [10]. The TiC nanoparticles cause changes in spectra of PVA-CMC, which include shift in some bonds and change in the intensities. These changes attributed to interactions of nanoparticles with polymers. The FT-IR studies show the non-interactions between PVA-CMC polymer matrix and TiC nanoparticles [11].

The variation of dielectric constant for PVA-CMC-TiC nanocomposites with frequency at different concentrations of TiC nanoparticles is shown in Fig. 2.

The polarized molecules or atoms in dielectric medium can align in accordance with the applied electric field, which implies electro-

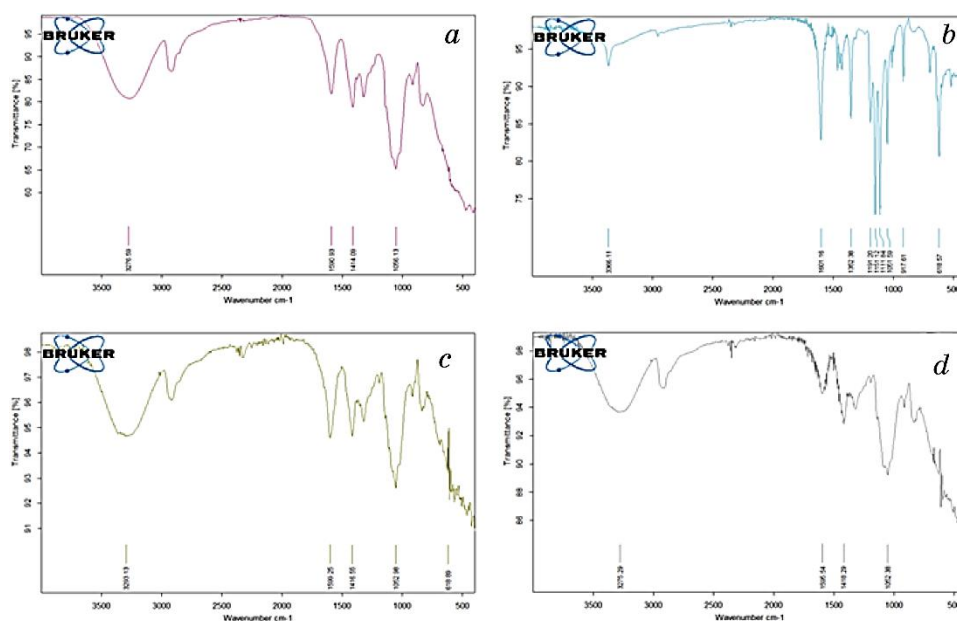


Fig. 1. FT-IR spectra for PVA-CMC-TiC nanocomposites: *a*) pure blend; *b*) 1 wt.% TiC nanoparticles; *c*) 2 wt.% TiC nanoparticles; *d*) 3 wt.% TiC nanoparticles.

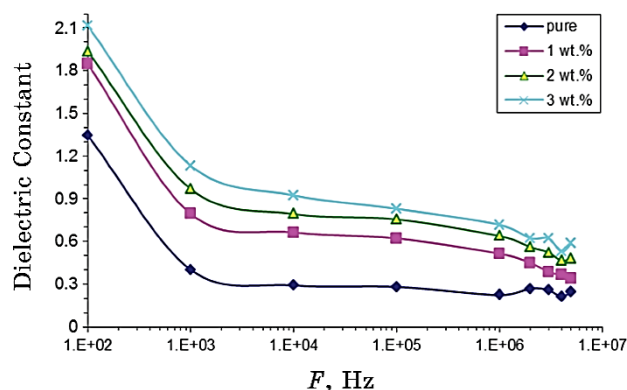


Fig. 2. Variation of dielectric constant for PVA–CMC–TiC nanocomposites with frequency at room temperature.

magnetic energy to be transferred into materials. In Figure 2, the behaviour of frequency-dependent dielectric constant of PVA–CMC–TiC nanocomposites at room temperature is illustrated. The plot inferred that the value of dielectric constant has a strong influence in radiofrequency region. At lower frequencies, high values are noticed that indicates that the four polarizations are active, whereas at higher frequencies, due to the high periodic field reversal resulting in inertia of the dipolar moments, causes the reduction in the values. An independent frequency trace is noticed beyond 1 kHz but a substantial modification is achieved by the incorporation of TiC nanoparticles in the matrix. A giant polarizability is noticed because the particles are relatively free to move in extended trajectories between the electrodes. The TiC exhibits a strong ionic polarization due to the titanium and carbon ions and has a high value of static permittivity, so that the increment in the values of relative permittivity for the composites due to these mobile charge carriers is expected.

Figure 3 shows the frequency-dependent dielectric loss of PVA–CMC–TiC at room temperature. This curve possessed a similar trace as the plot of dielectric constant, and the changes in steepness are observed at the same frequency region. This phenomenon can be identified as interfacial polarization (IP) where the high values are presented at the low-frequency region. At higher frequencies, the dipoles cause an inertia results from the electrical heterogeneity known as Maxwell–Wagner–Sillars effect [12].

As shown in Figures 2, 3, the dielectric constant of PVA–CMC blend increases with increase in TiC nanoparticles' concentration; this behaviour could be interpreted from both interfacial polarization inside the nanocomposite in applied alternating electric field

and increase of the charge carriers.

The dielectric loss increases with increase in concentrations for nanoparticles. The increase of dielectric loss of PVA–CMC blend with increase in TiC nanoparticles' concentration for related to the increase of the number for charge carriers. At low concentrations of TiC nanoparticles, they are formed as clusters; when the concentra-

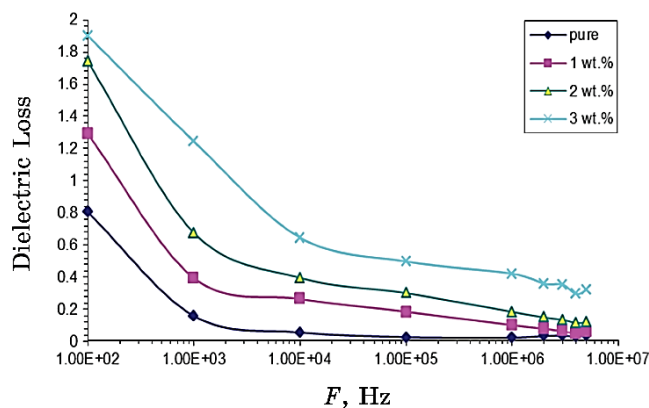


Fig. 3. Variation of dielectric loss for PVA–CMC–TiC nanocomposites with frequency at room temperature.

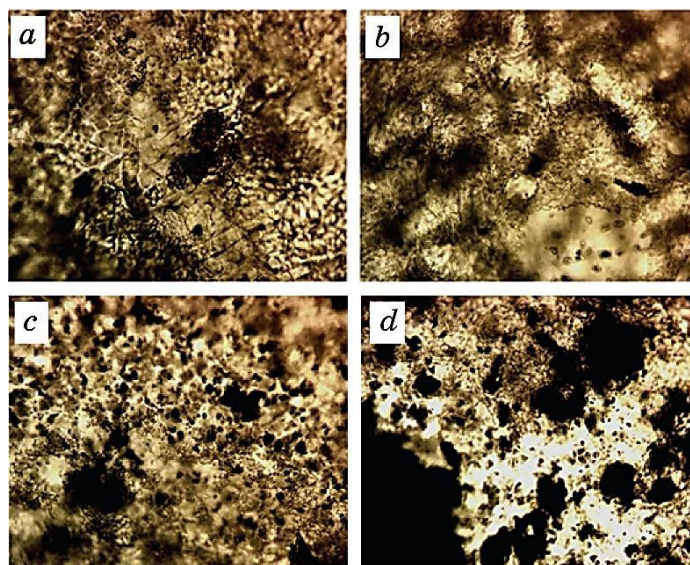


Fig. 4. Photomicrographs ($\times 10$) for PVA–CMC–TiC nanocomposites: *a*) for pure; *b*) for 1 wt.% TiC nanoparticles; *c*) for 2 wt.% TiC nanoparticles; *d*) for 3 wt.% TiC nanoparticles.

tion of TiC nanoparticles increases, the nanoparticles form a continuous network in the nanocomposite [11], as shown in Fig. 4. In Figure 4, the TiC nanoparticles' arrangement in PVA-CMC polymer matrix is shown at magnification power ($\times 10$). The TiC nanoparticles are aggregated as clusters at low concentrations. When increasing the concentrations of TiC nanoparticles, the nanoparticles form a continuous network inside the PVA-CMC blend [11].

The variation of A.C. electrical conductivity for PVA-CMC-TiC nanocomposites with frequency for different TiC nanoparticles' concentrations is shown in Fig. 5. The increase in A.C. conductivity is due to increase in the composition of the TiC nanoparticles' concentration in polymer matrix resulting in relatively more number of free charges carriers. These charge carriers move in the amorphous polymer matrix, and hence the conductivity increases. Thus, there is a relation between the amorphous nature of the polymer film and the conductivity [13].

In addition, the A.C. conductivity increases as TiC nanoparticles' concentration increases. This result can be attributed to an increase in the conductivity because of the increase in the charge carrier density in the polymer blend and the increase of the free charge carrier number [14].

Figure 6 shows variation of resistance for PVA-CMC-TiC nanocomposites with compression stress. Pressure sensors, which are widely applied in automation equipment, robot arms, touch panels, and cell phones, have been developed on the basis of piezoresistive, piezoelectric, and capacitive principle. Pressure sensors need high sensitivity and strong discriminatory abilities for wide applications

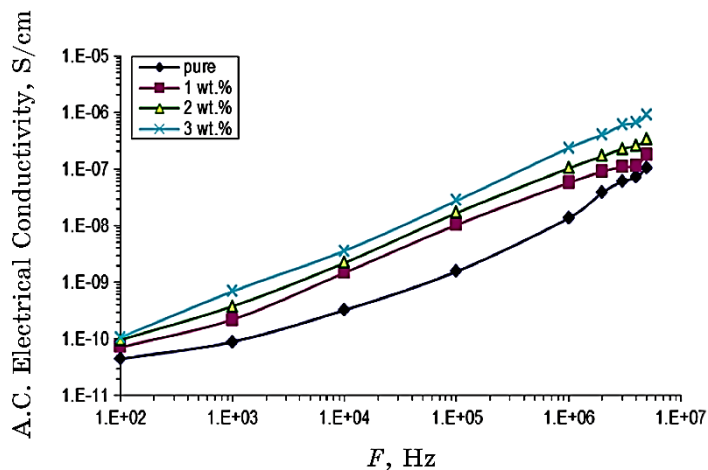


Fig. 5. Variation of A.C. electrical conductivity for PVA-CMC-TiC nanocomposites with frequency at room temperature.

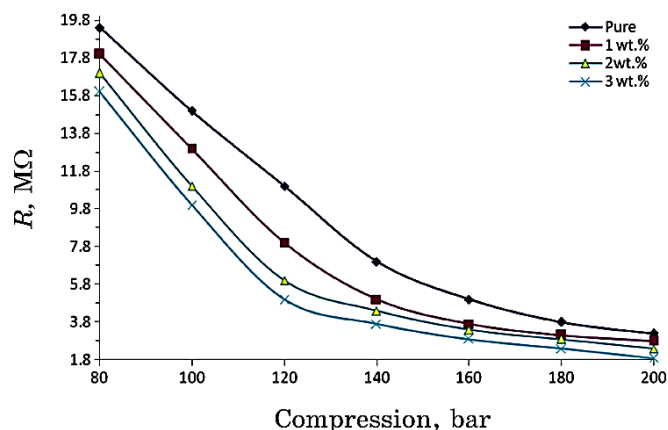


Fig. 6. Variation of resistance for PVA–CMC–TiC nanocomposites with compression.

[15]. As shown in Figure 6, the resistance for PVA–CMC–TiC nanocomposites decreases with increases in compression stress. This behaviour can be explained as follows: when stress is applied, it will change the local dipole distributions and induce an electric field; the induced electric field accumulates the charges at both the top and the bottom of the sample [16].

4. CONCLUSIONS

The dielectric constant, dielectric loss, and A.C. electrical conductivity of PVA–CMC blend increase with increasing titanium carbide nanoparticles' concentration.

The dielectric constant and dielectric loss of PVA–CMC–TiC nanocomposites decrease with increase of the frequency.

The A.C. electrical conductivity increases with increase of the frequency.

The PVA–CMC–TiC nanocomposites films have high sensitivity for pressure.

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