Extended Abstract

Controlling of Impedance Values of Liquid Crystal Samples Containing Tin Oxide Nanoparticles under the Influence of Oxygen Plasma

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Abstract

In this study, the effect of incorporating tin oxide nanoparticles and their surface modification was investigated by oxygen plasma on the impedance behavior of a nematic liquid crystal. Samples were prepared without plasma treatment and after oxygen plasma exposure for 2 and 14 minutes. Impedance spectra were recorded over the frequency range of 0.1 Hz to 0.1 MHz using an equivalent circuit model consisting of bulk resistance (R_{LC}), bulk capacitance (C_{LC}), double-layer capacitance (C_{DL}), and a Warburg element (W). The results revealed that the addition of SnO_2 nanoparticles decreases resistance and enhances conductivity, whereas plasma treatment increases the charge-transfer barriers due to the formation of a thin oxide shell on the particle surface. SEM images confirmed that the mean particle size increases from 28 nm to 32 nm after 2 min and to 34 nm after 14 min of plasma treatment. The observed variations in C_{DL} and W indicate that ionic diffusion and molecular ordering are modified with increasing plasma time. Overall, controlling plasma conditions provides an effective approach for tailoring the electrical response and optimizing the performance of nanoparticle-doped nematic liquid crystals for use in sensors and advanced display technologies.

Keywords: Oxygen, Liquid crystal, Plasma, Resistance, Nanoparticle, Capacitance.

1. INTRODUCTION

Liquid crystals are materials with properties between crystalline solids and isotropic liquids, making them widely used in displays, sensors, and photonic devices [1-3]. Their electro-optical performance depends strongly on electrical and dielectric properties such as conductivity, polarization, and impedance. A common approach to improve these properties is doping liquid crystals with nanoparticles. Due to their high surface area

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and strong interfacial effects, nanoparticles can significantly modify molecular alignment, charge transport and dielectric behavior [4-6]. Among them, SnO_2 nanoparticles are widely used because of their good conductivity, stability, and semiconducting nature, which enhance charge transfer and overall device performance. Plasma treatment is another effective and eco-friendly method for surface modification. It can activate nanoparticle surfaces and create oxide layers without chemical additives, thereby influencing their interaction with liquid crystal molecules and affecting impedance and polarization behavior. While previous studies mainly used argon plasma for physical modifications, oxygen plasma introduces stronger chemical changes such as oxygen functional groups and oxide formation. In this study, we investigated the effect of oxygen plasma exposure time on the resistance, capacitance, and ionic diffusion of SnO_2-doped nematic liquid crystals.

2. Experimental Section

ML-0648 nematic liquid crystal and SnO_2 nanoparticles (Merck) were used. The liquid crystal had a nematic-to-isotropic transition temperature of 354.15 K and birefringence of 0.1029, while SnO_2 nanoparticles had an average size of 28 nm. Parallel liquid crystal cells were prepared using ITO-coated glass substrates, which were cleaned with water, acetone, and ethanol. Alignment layers were applied to ensure uniform molecular orientation, and the cells were filled with pure and nanoparticle-doped samples. Impedance measurements were carried out using an Autolab PGSTAT302 system at room temperature, and morphology was studied using SEM (JSM-7600F). Oxygen plasma treatment was performed in a radio-frequency reactor (13.56 MHz, 50 W). The chamber was evacuated to 0.001 Torr, then filled with oxygen gas up to 0.50 Torr to generate a stable plasma. Nanoparticles were treated for 2 and 14 minutes to study the effect of exposure time on structure and electrical behavior. SEM results showed minimal changes at short times, while longer exposure led to agglomeration; therefore, 2 and 14 minutes were selected as the main treatment conditions.

3. RESULTS AND DISCUSSION

Electrochemical impedance spectroscopy was used to investigate the dynamic electrical response of the liquid crystal systems. The total impedance is expressed as a complex quantity composed of real and imaginary components:

$$|Z| = \sqrt{Z_r^2 + Z_i^2} \tag{1}$$

The impedance spectra showed a strong dependence on frequency, nanoparticle incorporation, and plasma treatment duration. As the frequency increased, both the total impedance and the real component decreased and eventually approached constant values at high frequencies, indicating the dominance of ohmic conduction and the reduction of interfacial polarization effects. The imaginary component initially decreased and then increased with frequency before stabilizing at high frequencies. Compared with pure liquid crystal samples, the SnO_2-doped samples exhibited a shift in impedance behavior toward lower frequencies. This shift indicates longer charge relaxation times and stronger interfacial polarization effects. The nanoparticles created charge trapping centers and modified the interaction between liquid crystal molecules and interfaces, leading to slower charge transport dynamics. The real component of impedance represents the electrical resistance of the system and is

directly related to ionic conductivity and charge carrier density. At low frequencies, ions have sufficient time to accumulate near interfaces, producing higher apparent resistance. Increasing the frequency suppresses this polarization effect and reduces the effective resistance. The imaginary component is associated with capacitive behavior. At moderate frequencies, molecular polarization becomes more effective, while at high frequencies the dipoles can no longer follow the rapidly varying electric field. The addition of SnO_2 nanoparticles increased ionic conductivity by facilitating ion mobility and enhancing surface polarization. However, oxygen plasma treatment significantly altered this behavior. SEM images revealed that the average nanoparticle size increased from 28 nm in untreated samples to approximately 32 nm after 2 minutes and 34 nm after 14 minutes of plasma exposure. The formation of thicker oxide layers reduced the number of active surface sites and increased the internal resistance of the nanocomposite system. Cole–Cole plots confirmed these observations (Fig. 1).

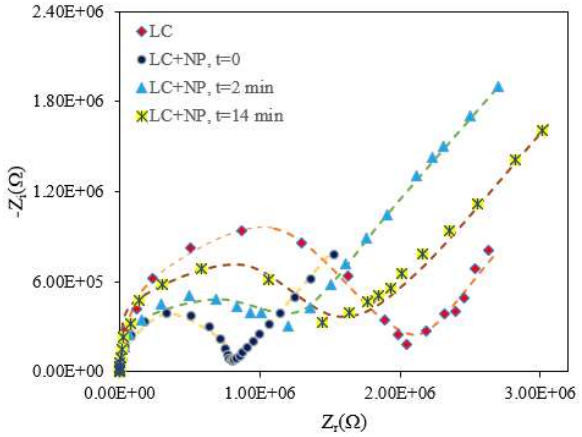


Fig. 1. Cole-Cole curves of studied samples.

Plasma-treated samples exhibited semicircle larger diameters, indicating higher resistance values. Pure liquid crystal showed semicircle samples the largest of their because highly ordered molecular structure and lower charge mobility. An equivalent circuit model consisting of bulk resistance, liquid crystal capacitance, double-layer capacitance, and a Warburg diffusion element was used to analyze the impedance data (Table 1).

Sample	R_{LC} (MΩ)	C_{LC} (nF)	C_{DL}(μF)	W_{sr}(MΩS$^{-0.5}$)
LC	2.04	3.18	1.027	1.01
LC+ NP (t=0)	0.75	0.23	0.001	3.21
LC+ NP (t=2 min)	0.94	1.69	0.007	9.82
LC+ NP (t=14 min)	1.56	4.54	0.060	2.37

Table 1. Results obtained from fitting the Cole–Cole plots using the equivalent circuit model.

The untreated nanoparticle-doped sample exhibited the lowest resistance because semiconducting nanoparticles created additional charge transport pathways. Plasma treatment increased resistance due to oxide layer growth and reduced carrier mobility. Capacitance values increased after plasma exposure because oxygen-containing functional groups enhanced local polarization effects. In contrast, the double-layer capacitance decreased in plasma-treated samples because surface modification disrupted charge accumulation near the electrode interfaces. The Warburg diffusion parameter and ionic diffusion coefficient were also strongly influenced by plasma treatment. Ionic diffusion was highest in the pure liquid crystal and decreased significantly after nanoparticle incorporation. The 2-minute plasma treatment produced the lowest diffusion coefficient, indicating maximum restriction of ionic motion. After 14 minutes of treatment, diffusion partially recovered because of changes in surface activity and diffusion pathways.

These findings demonstrate that oxygen plasma treatment can effectively control charge transport, polarization behavior, and ionic diffusion in liquid crystal nanocomposites through surface engineering of SnO_2 nanoparticles.

4. Conclusion

This study experimentally investigated the influence of SnO_2 nanoparticles and oxygen plasma surface treatment on the impedance behavior of nematic liquid crystals. The results showed that nanoparticle incorporation enhanced electrical conductivity and reduced system resistance by creating additional charge transport pathways. However, oxygen plasma treatment produced uniform oxide layers on the nanoparticle surfaces, increasing charge transfer barriers and modifying the capacitive and diffusion characteristics of the composites. Increasing plasma exposure time from 2 to 14 minutes changed nanoparticle morphology and increased particle size, which directly affected molecular ordering, polarization behavior, and charge distribution inside the liquid crystal matrix. These modifications were clearly reflected in the equivalent circuit parameters, capacitance values, and Warburg diffusion behavior. The study demonstrates that plasma-assisted surface engineering is an effective method for tuning the electrical and impedance properties of liquid crystal nanocomposites. Such controllable behavior makes these materials promising candidates for advanced electro-optical devices, fast-response sensors, photonic systems, and smart functional materials.

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