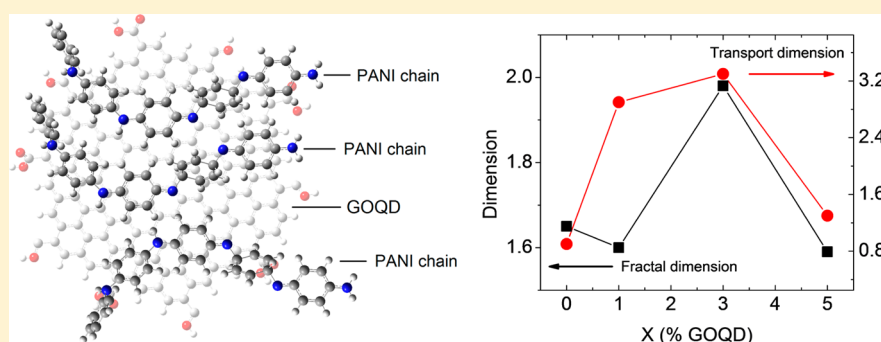


Tuning Electrical Transport Mechanism of Polyaniline–Graphene Oxide Quantum Dots Nanocomposites for Potential Electronic Device Applications

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ABSTRACT: In this report, we study the tuning of the electrical transport dimensionality of polyaniline–graphene oxide quantum dots nanocomposites (PANI-GOQD) for electronic device applications. We focused this study on the microstructure and its correlations with electrical transport properties. X-ray diffraction and small-angle X-ray scattering analyses showed the effect that caused the addition of GOQD on the structural and microstructural properties of polyaniline. Confocal Raman spectroscopy revealed that the presence of GOQD leads to a notorious decrease of the polaron population of polyaniline. In relation to this experimental evidence, a significant increase in resistivity was observed for PANI-GOQD nanocomposites with respect to pure polyaniline. Electrical transport showed a typical Arrhenius behavior at relatively high temperatures and a broad transition with a logarithmic dependence of the activation energy with temperature for the intermediate temperature regime. Additionally, PANI-GOQD showed an increase in the hopping transport dimensionality even in the case of low amounts of GOQD. The tuning of this dimensionality in these nanocomposites could be important for the development of novel organic electronic materials.

1. INTRODUCTION

There is a recent interest in the preparation and characterization of conductive polymer based devices for electronic,¹ photoresponse,² and energy conversion³ applications. Polyaniline (PANI) has shown excellent processing and electrical properties among other conductive polymers for potential electronic device applications.^{4–6} There are recent reports on the preparation and electrical transport properties of PANI nanocomposites with additions of different materials such as oxide nanoparticles^{7,8} or carbon-based nanostructures.^{9,10} These experimental and theoretical reports study the electrical transport mechanism of these polyaniline based materials. The preparation and electrical characterization of polyaniline–graphene oxide quantum dots (PANI-GOQD) nanocomposites has been recently reported as promising materials for optical^{11,12} and supercapacitor electrode^{13,14} applications. However, studies regarding the electrical transport mechanism and charge carrier dimensionality in these PANI-GOQD nanocomposites are still to be performed. Although it is accepted that the electrical transport mechanism is based mainly on the hopping process of charge carriers,⁵ the possible correlation with microstructure remains open. In fact, the

effects of GOQD additions, due to their low dimensionality with respect to graphene oxide (GO), could have consequences in the electrical transport dimensionality of PANI-GOQD nanocomposites. Since small-angle X-ray scattering (SAXS) is usually performed to study the nanoparticles size, correlation distances, and fractal dimensions; this technique is useful to correlate the last one with electrical transport dimensionality. Additionally, there are very few experimental correlations between the polaron populations and the electrical transport properties in these conductive polymer nanocomposites.¹⁵ Raman spectroscopy, which is another powerful tool to characterize the formation of polarons in polyaniline, could be used as a key technique for that purpose.

This report is about the preparation and microstructure characterization of PANI-GOQD nanocomposites by means of X-ray powder diffraction, small-angle X-ray scattering, and confocal Raman spectroscopy. Here we correlate microstructural characterization with the electrical transport perform-

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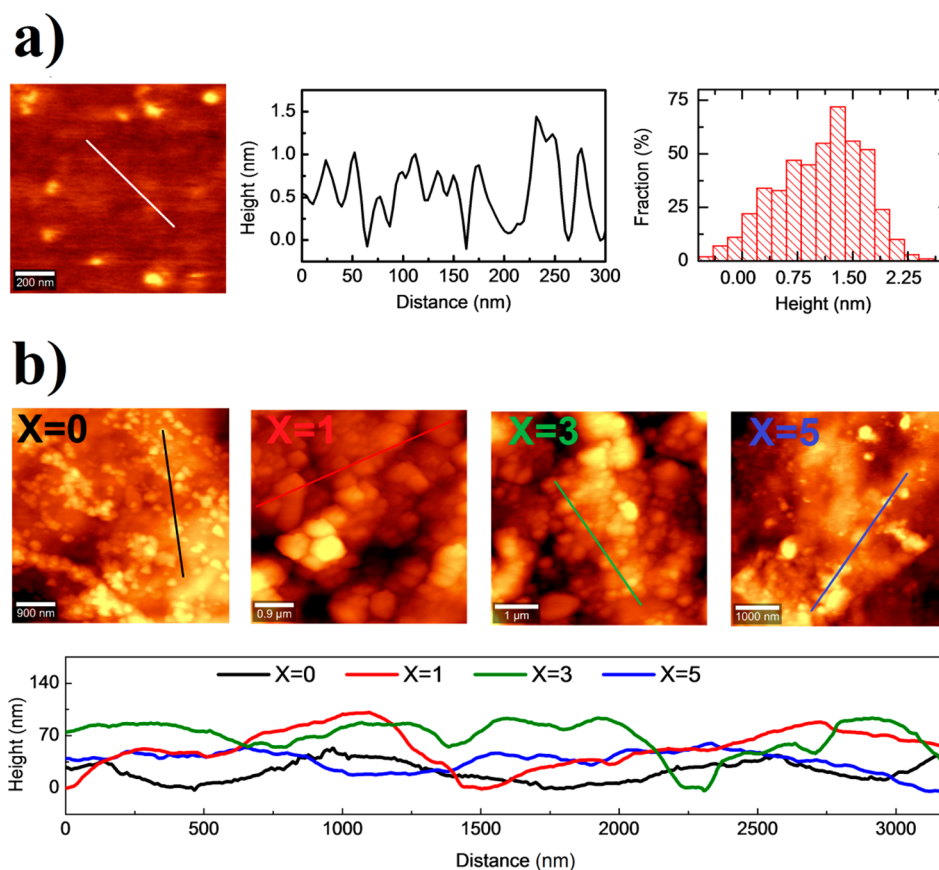


Figure 1. AFM images for (a) GOQD samples and (b) PANI-GOQD-*X* nanocomposites with *X* = 0, 1, 3, and 5. Topography analysis was obtained from the cross-section marked with lines in the images. GOQD histogram shown in (a) was obtained from a large representative cross-section.

ance in order to reveal the transport mechanism in these conductive polymer nanocomposite systems.

2. MATERIALS AND METHODS

2.1. Preparation of GOQD. Graphene oxide quantum dots were prepared using graphene oxide (GO) as precursor using the sonoFenton method.¹⁶ GO precursor was prepared using the Hummer's modified method.¹⁷ GOQD preparation starts with 20 mL of H₂O₂ (30%) and 10 mg of FeCl₃ added to 50 mg of GO precursor dispersion in 100 mL of distilled water, under stirring at room temperature. The solution was submitted to ultrasonic treatment working at a fixed power of 90 W during 4 h. The graphene oxide quantum dots (GOQD) solution was finally dialyzed for 3 days in order to remove residual iron.

2.2. Preparation of PANI-GOQD-*X* Nanocomposites. GOQD aqueous solution was dried at 100 °C for several hours to remove residual water and resuspended in 10 mL of tetrahydrofuran with different amounts of GOQD additions. PANI emeraldine salt (PANI-DBSA-H₂SO₄) with average Mw ≈ 15,000 provided by Sigma-Aldrich CAS No. 428329 was suspended separately in 10 mL of tetrahydrofuran and then added to the GOQD different suspensions. PANI and GOQD mixed suspensions were vigorously stirred and heated at *T* = 70 °C for 10 h until dryness to remove residual solvent. In this report, nanocomposites were studied with the following GOQD weight fraction additions: 0, 1, 3, and 5% w/w, named as PANI-GOQD-*X* with *X* = 0, 1, 3, and 5, respectively. The PANI-GOQD dried powder was then grinded and

compressed at 50 kN for 10 min to form pellets with a ~800 μm thickness and 12 mm diameter.

2.3. Characterization. PANI-GOQD-*X* nanocomposites were studied by X-ray diffraction (XRD) using a Rigaku Ultima IV diffractometer working in Bragg–Brentano configuration with CuKα radiation in the 2θ = 5–50° range using 2θ steps of 0.02° with a 5 s integration time per step. Grazing incidence small-angle X-ray scattering (SAXS) was performed using Rigaku Ultima IV diffraction system working in parallel beam configuration with CuKα radiation in the *q* = 0.01–0.5 Å^{−1} range and fixed incident angle at 0.2° with respect to the critical angle. Differential scanning calorimetry (DSC) was performed using Shimadzu DSC-60 differential scanning calorimeter using nitrogen 50 mL/min flow at the temperature range *T* = 25–200 °C with a ramp rate of 5°/min. Atomic force microscopy (AFM) in the AC mode and confocal Raman spectroscopy was performed using WITec Alpha 300-RA. AFM and Raman data acquisition for GOQD sample was obtained by placing a droplet of the GOQD suspension on a silicon substrate and drying at ~180 °C for 15 min. Raman spectra for PANI-GOQD-*X* nanocomposites were collected using a 532 nm laser wavelength, and the laser power was adjusted at ~3 mW to avoid polyaniline decomposition. For each case, a set of 20 spectra of 0.2 s integration time were averaged. AC impedance spectroscopy analysis was performed for the PANI-GOQD-*X* pellets using stainless steel electrodes. The applied a.c. voltage amplitude was 10 mV in the 0.01 Hz–1 MHz frequency regime at *T* = 300 K using a Gamry Reference 3000 impedance analyzer. DC conductivity versus temperature measurements

was obtained using the four-probe technique in the temperature range 12–310 K using a Janis CCS-150 cryogenic system.

3. RESULTS AND DISCUSSION

AFM topography analysis for GOQD samples is shown in Figure 1a. The height of GOQD samples across a large cross-section line showed a bimodal distribution with $h_1 \approx 0.65$ and $h_2 \approx 1.25$ nm, which is in agreement with single-layer and bilayer GOQD thickness, respectively. Moreover, a rough estimation of the width of peaks (D) from the topography analysis shown in Figure 1a leads to $D \approx 20$ –40 nm, which can be associated with GOQD mean diameter size, as already reported.¹⁸ Additionally, the agglomeration of GOQD into higher-sized clusters was also observed, probably as a consequence of the drying process for the sample preparation for AFM measurements. AFM topography analysis for PANI-GOQD-X nanocomposite pellet surfaces is shown in Figure 1b. The presence of ~ 20 –80 nm size nanometric nodules were observed, probably in relation to polyaniline fibers clustering as already observed in previous reports.¹⁹

Grazing incidence small-angle X-ray scattering (GI-SAXS) curves for PANI-GOQD-X are shown in Figure 2. In all cases, a

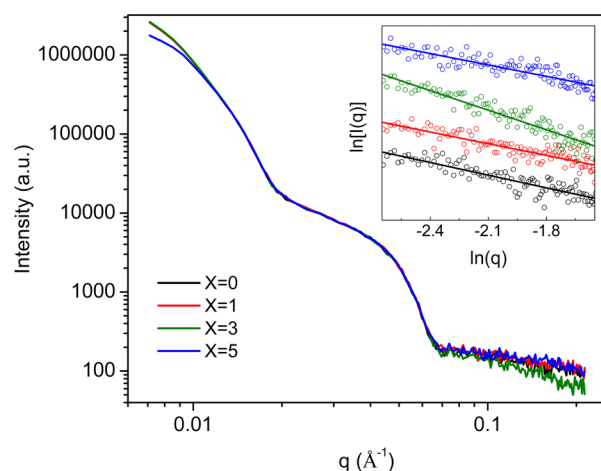


Figure 2. GI-SAXS analysis for PANI-GOQD-X with $X = 0, 1, 3$, and 5 . The $\ln[I(q)]$ vs $\ln(q)$ plots and linear fit at high- q region is shown in the inset.

well-defined bump was observed at the low- q region, suggesting the presence of ~ 25 nm clusters that could be explained by the presence of nanometric polyaniline clusters, in agreement with those observed using AFM analysis. At mid- q region, another bump was observed, suggesting the presence of a second size population of ~ 9 nm scatterers or also to a possible ~ 9 nm correlation length between nanofibers. At high- q region, SAXS curves usually follow an $I(q) \approx q^{-P}$ dependence, with P related to the sample fractal dimension (D) following:²⁰

$$D = P + 1 \text{ for } 0 < P < 2$$

$$D = 6 - (P + 1) \text{ for } 2 < P < 3$$

In all cases, SAXS analysis for PANI-GOQD-X at high- q region showed fractal dimension $D \approx 1.7, 1.6, 2.0$, and 1.6 for $X = 0, 1, 3$, and 5 , respectively, as summarized in Table 1. This is suggesting that the addition of GOQD does not drastically modify the fractal dimension of PANI-GOQD-X nanocomposites. The fractal dimension (D) ranged between one and two-dimensional values are suggesting that PANI-GOQD-

Table 1. XRD and SAXS Analysis for PANI-GOQD-X with $X = 0, 1, 3$, and 5 ^a

	$X = 0$	$X = 1$	$X = 3$	$X = 5$
d_1 (Å)	5.6(10)	5.7(11)	5.7(9)	5.7(14)
d_2 (Å)			4.7(7)	4.7(1)
d_3 (Å)	4.4(3)	4.5(6)	4.5(4)	4.4(6)
d_4 (Å)	3.5(1)	3.5(2)	3.5(1)	3.5(1)
P	0.65(3)	0.60(3)	1.00(4)	0.59(3)
D	1.65(3)	1.60(3)	2.00(4)	1.59(3)

^aMean correlation lengths (d) and errors in parentheses were obtained following $d = \lambda/2 \sin(\theta)$ from Lorentzian deconvolution of XRD patterns. The fractal dimension (D) was obtained following $D = P + 1$ from the high- q region $\ln[I(q)]$ vs $\ln(q)$ linear fit.

X samples are not a perfectly one-dimensional arrangement of polyaniline fibers but rather an array of fibers with a certain rugosity which leads to a fractal microstructural pattern. However, it is important to remark that the addition of low amounts of GOQD do not seem to drastically modify this fractal pattern, remaining in intermediate D values between one and two dimensions.

X-ray powder diffraction (XRD) patterns for PANI-GOQD-X nanocomposites are shown in Figure 3a, and mean

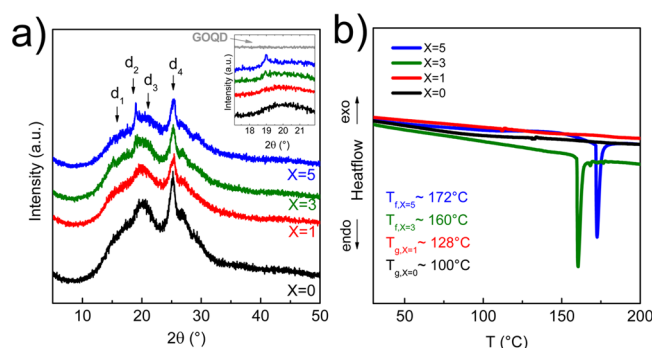


Figure 3. (a) XRD patterns and (b) DSC profiles for PANI-GOQD-X with $X = 0, 1, 3$, and 5 . XRD mean correlation peaks are marked as d_1 , d_2 , d_3 , and d_4 . A zoom of the d_2 peak for PANI-GOQD-X is shown in the inset in which GOQD data is included for comparison to show the absence of this peak.

correlation distances are summarized in Table 1. $X = 0$ sample showed typical XRD profile for pure polyaniline in its emeraldine salt conformation. In this case, XRD pattern consists of two broad peaks at $2\theta = 15.4^\circ, 19.8^\circ$ and a sharper peak at $2\theta = 25.2^\circ$, with associated mean coherence distances $d \approx 6.0, 4.4$, and 3.5 Å, respectively.^{21,22} However, the appearance of a new sharp peak at $2\theta = 19.0^\circ$ with associated mean coherence distance $d \approx 4.6$ Å is observed for PANI-GOQD-X, and its relative intensity increases with increasing GOQD additions. XRD analysis for GOQD samples showed no diffraction peaks in agreement with a highly amorphous structure revealing that the new peak is absent in pure GOQD, as shown in Figure 3a-inset. The new peak at $2\theta \approx 19^\circ$ with associated $d \approx 4.6$ Å mean coherence distance could be associated with the transition from the polyaniline from polaron to bipolaron configuration²¹ as a consequence of the GOQD interaction with polyaniline. However, the new peak at $\sim 19^\circ$ is sharp enough to also consider the possibility of GOQD blending and location between polyaniline adjacent chains via

π - π stacking interaction leading to an enhancement on the degree of order in the polymer structure.²²

Differential scanning calorimetry (DSC) analysis for PANI-GOQD-X is shown in Figure 3b. The glass transition temperature (T_g) estimated from the DSC curves were $T_g \approx 100$ and 128 °C for $X = 0$ and 1 , respectively. Moreover, $X = 3$ and 5 showed a well-defined endothermic peak associated with the melting process (T_f) of crystalline zones in PANI-GOQD-X nanocomposites at $T_f \approx 160$ and 172 °C, respectively. In both cases, the increase of both T_g and T_f with increasing X is suggesting an increase in the degree of order of polyaniline fibers for higher amounts of GOQD additions. The increase in the degree of order with increasing X is also consistent with the appearance of the new sharp peak at $2\theta \approx 19^\circ$ in the XRD patterns, observed for higher amounts of GOQD additions.

Raman spectra for PANI-GOQD-X are shown in Figure 4a, and both the vibrational modes frequencies and assignments are summarized in Table 2. Raman spectra for pure GOQD showed two typical broad peaks at ~ 1344 and 1599 cm^{-1} , ascribed to D and G modes, respectively. Both the frequency and width of peaks are in agreement with GOQD with a 20–30 nm diameter size according to a systematic study already reported.²³ However, Raman spectra for pure PANI showed peaks at ~ 1167 and 1260 cm^{-1} ascribed to C–H bending modes of the aromatic ring, at ~ 1334 cm^{-1} to the polaron C–N⁺ stretching mode, at ~ 1415 and 1486 cm^{-1} to C–N and C=N stretching modes, and at ~ 1580 and 1636 cm^{-1} ascribed to C–C and C=C stretching mode of the aromatic ring.^{24,25} However, the peak ascribed to the polaron C–N⁺ stretching mode for PANI-GOQD-X showed a remarkable decrease in its relative intensity with GOQD additions, as shown in Figure 4b. This observation is suggesting that the GOQD addition is somehow interacting with the charge carriers of polyaniline leading to a suppression of the polaron population. PANI-GOQD-X with $X = 3$ and 5 showed an increase of GOQD peaks at ~ 1344 and 1599 cm^{-1} , as a mere consequence of its increasing concentration. Nevertheless, the peak at ~ 1167 cm^{-1} showed a shift to higher frequencies at ~ 1186 cm^{-1} with GOQD additions, probably associated with the transition of the polaron to the bipolaron conformation, as it was previously reported in our previous study using density functional theory (DFT) simulations.¹⁵

Impedance spectroscopy analysis for PANI-GOQD-X nanocomposites is shown in Figure 5. Phase (ϕ) versus frequency plots showed zero values for a wide range of frequencies ($f = 10^{-2}$ – 10^5 Hz) suggesting a resistive behavior. The positive ϕ values observed at higher frequencies ($f > 10^5$ Hz) are probably attributed to a small inductance behavior associated with the device wires contribution. Impedance modulus also showed constant impedance values in a broad frequency regime with $Z \approx 8$, 10 , 30 , and 90 $\text{ohm}\cdot\text{cm}$ for $X = 0$, 1 , 3 , and 5 , respectively. The increase in the impedance modulus was observed with increasing GOQD additions, in agreement with the decrease in the polaron population envisaged by our Raman analysis discussed above. In all cases, a moderate decrease in the impedance was observed for the low frequency regime, as already observed for other polyaniline composites.²⁶

Resistivity versus temperature curves for PANI-GOQD-X nanocomposites are shown in Figure 6. A typical semiconductor behavior was observed for all cases, denoted by an exponential increase of resistivity with decreasing temperature. In addition, an increase in the resistivity with increasing GOQD additions was observed for the entire temperature regime

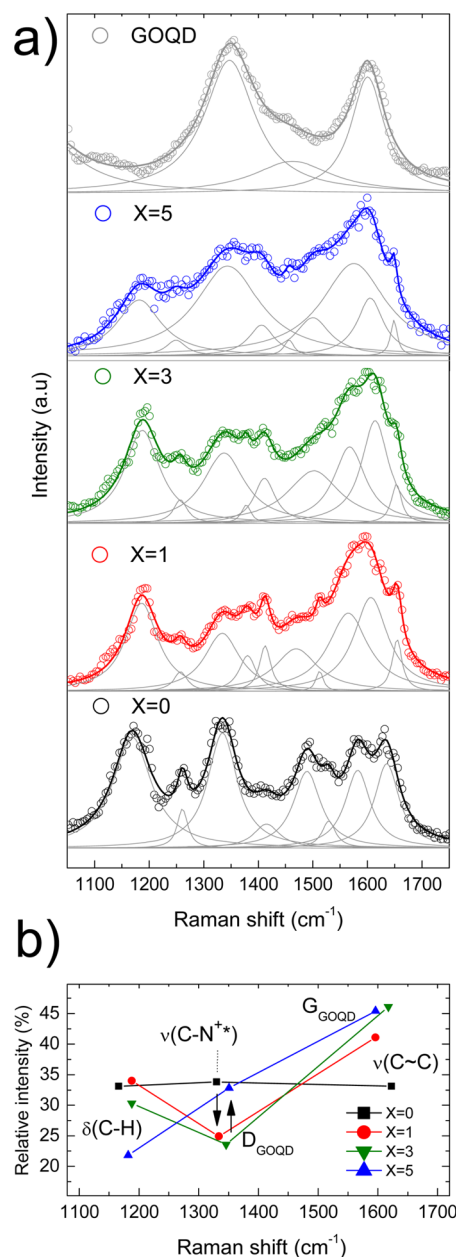


Figure 4. (a) Raman spectra and Lorentzian deconvolution for GOQD and PANI-GOQD-X with $X = 0, 1, 3$, and 5 . (b) Raman relative intensity and shift of frequencies for main selected peaks.

analyzed. This is also in agreement with the decrease of polaron population with increasing GOQD additions, envisaged by the Raman analysis. The higher temperature regime (~ 300 – 255 K) can be described using the Arrhenius law, which can be expressed by the following equation:

$$\sigma(T) \approx \exp\left(-\frac{E_{a,0}}{k_B T}\right) \quad T > T_1 \approx 255 \text{ K}$$

for which σ is the dc conductivity, $E_{a,0}$ is the activation energy, and k_B is the Boltzmann constant. The linearization of Arrhenius equation represented by the $\ln(\sigma)$ vs T^{-1} plots are shown in Figure 7. In all cases, the linear fit showed no drastic apartment from linearity in the $T > T_1$ temperature regime. The activation energy ($E_{a,0}$) obtained from the slope of the linear region of $\ln(\sigma)$ vs T^{-1} plots for PANI-GOQD-X is shown in

Table 2. Raman Spectra Analysis for Pure GOQD and PANI-GOQD-X with X = 0, 1, 3, and 5^a

X = 0	X = 1	X = 3	X = 5	GOQD	assignment
1171(1)s	1188(1)s	1188(1)s	1184(3)s		polyaniline $\delta(\text{C-H})$
1260(1)w	1266(3)w	1256(2)w	1248(5)w		
1334(1)s	1334(4)m	1334(4)m			polyaniline $\nu(\text{C-N}^+\bullet)$
	1380(3)w	1360(3)m	1348(7)s	1348(1)s	D mode
1417(4)m	1413(1)m	1409(2)m	1405(4)m		polyaniline $\nu(\text{C-N})$
1491(2)s	1474(5)s	1506(10)s	1503(6)s		polyaniline $\nu(\text{C=N})$
1580(2)s	1564(10)s	1567(4)s	1576(12)s		polyaniline $\nu(\text{C=C})$
	1605(6)m	1611(2)m	1603(4)m	1595(1)s	G mode
1636(2)w	1655(1)w	1652(1)w	1648(1)w		polyaniline $\nu(\text{C-C})$

^aExperimental Raman frequencies with measurement precision $\pm 3 \text{ cm}^{-1}$ and fit errors in parentheses were obtained from Lorentzian deconvolution of Raman peaks, and vibrational modes assignments were made in agreement with previous DFT Raman simulation.¹⁵

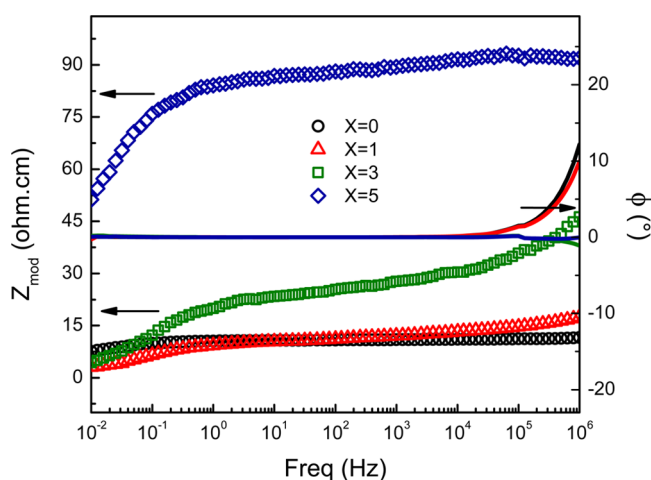


Figure 5. Impedance modulus (shapes) and phase (lines) versus frequency at room temperature ($T = 300 \text{ K}$) for PANI-GOQD-X with $X = 0, 1, 3$, and 5 .

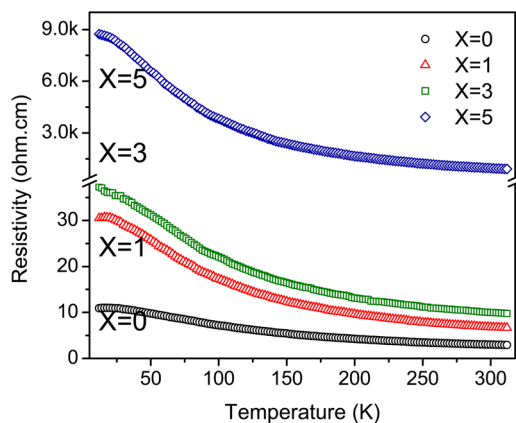


Figure 6. Resistivity versus temperature for PANI-GOQD-X with $X = 0, 1, 3$, and 5 .

Table 2. A decrease in the activation energy is observed with increasing GOQD additions with $E_{a,0} = 19.1, 18.5$, and 15.2 meV for $X = 0, 1$, and 3 , respectively. However, a drastic increase in the activation energy is observed for higher GOQD additions reaching $E_{a,0} = 30 \text{ meV}$ for $X = 5$.

The lower temperature regime ($T < 20 \text{ K}$) typically obeys the Shklovskii–Efros (ES) law ascribed to the electron–electron Coulombic gap observed at very low temperatures. However, the transition from Arrhenius to ES behavior is usually a broad transition, observed in the intermediate

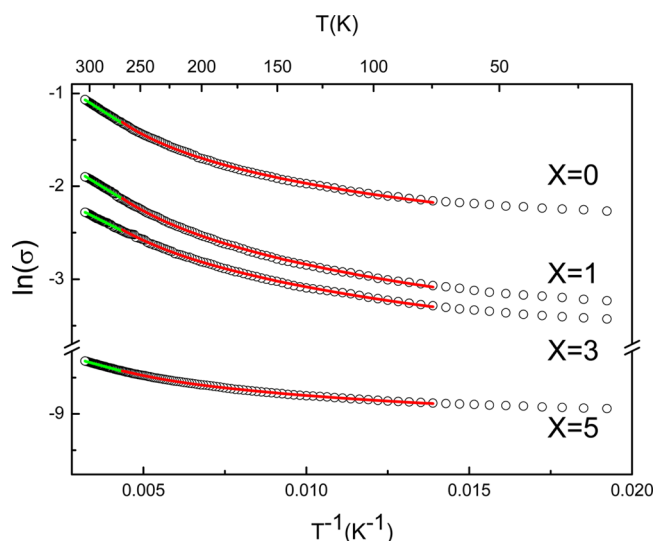


Figure 7. $\ln(\sigma)$ versus T^{-1} plots for PANI-GOQD-X with $X = 0, 1, 3$, and 5 . Linear and logarithmic fits are represented with green and red lines, respectively.

temperature regimes. Several approaches have been used to explain this temperature crossover such as the phenomenological scaling function prescribed by Aharony et al.²⁷ However, in our case, the intermediate temperature regime ($T \approx 255\text{--}70 \text{ K}$) showed good agreement with the Larkin and Khmel'nitskii prediction of a logarithmic dependence of the activation energy at intermediate temperature for disordered systems with large localization length.

$$\sigma(T) \approx \exp\left(-\frac{E_{a,1}}{k_B T} [\ln(\alpha T - \beta)]\right)$$

$$70 \text{ K} \approx T_2 < T < T_1 \approx 255 \text{ K}$$

with α and β depending on the localization length, hopping length, electric field, and pellet thickness.²⁸ PANI-GOQD-X with $X = 0, 1, 3$, and 5 showed excellent fits using the activation energy logarithmic dependence with temperature for the $T \approx 255\text{--}70 \text{ K}$ regime, suggesting that the transition from the Arrhenius to the ES behavior could be well described using the model proposed by Larkin and Khmel'nitskii. Based on this model, the length of the hop (x_0) should be equal to the localization length (L_c) at the transition temperature $T \approx T_1$ and x_0 increases in relation to L_c with decreasing temperatures ($T_2 < T < T_1$). It is important to remark that the transition temperature (T_1) remains approximately unchanged at $T_1 \approx$

255 K for all GOQD additions, suggesting that the length of hopping is not drastically affected by the presence of GOQD.

In order to study the dimensionality of the hopping process, we use the reduced activation energy (W), represented by the following equation:

$$W \approx \left(\frac{\partial \ln \sigma}{\partial \ln T} \right)$$

The $\log(W)$ versus $\log(T)$ plots are expected to be linear at relative high temperatures and its negative slope ($-\nu$) is widely used to determine the dimensionality of the hopping process (n) using $\nu = 1/(1 + n)$.^{29,30} The log–log plots for PANI-GOQD- X with $X = 0, 1, 3$, and 5 are shown in Figure 8, and the

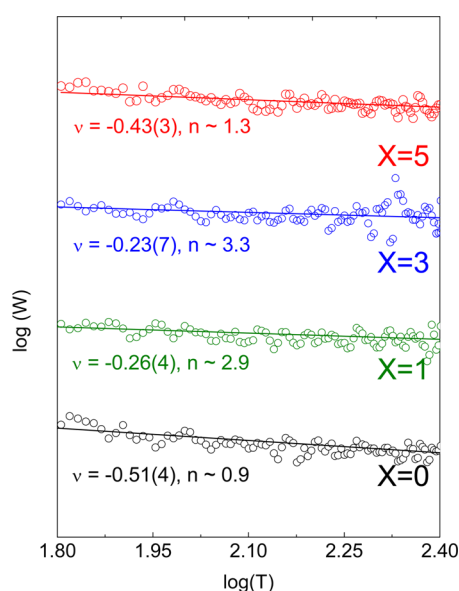


Figure 8. Reduced activation energy (W) versus temperature for PANI-GOQD- X with $X = 0, 1, 3$, and 5 . The transport dimensionality (n) is estimated from the slope (ν) using $n = (1/\nu) - 1$.

Table 3. Arrhenius Activation Energies and Reduced Activation Energy Analysis for PANI-GOQD- X with $X = 0, 1, 3$, and 5 ^a

	$X = 0$	$X = 1$	$X = 3$	$X = 5$
$E_{a,0}$ (meV)	19.06(12)	18.50(30)	15.15(22)	31.40(27)
$E_{a,1}$ (meV)	509(7)	643(9)	575(9)	862(11)
ν	−0.51(4)	−0.26(4)	−0.23(7)	−0.43(3)

^aArrhenius activation energies $E_{a,0}$ and $E_{a,1}$ and errors in parentheses were extracted from the slope of the linear fit ($T = 310$ – 255 K) and logarithmic fit ($T = 255$ – 70 K), respectively. The transport dimensionality factor (ν) and errors in parentheses was extracted from the slope of $\log W$ vs $\log T$ reduced activation energy plots.

slope (ν) estimation is summarized in Table 3. In all cases, the linear trend was observed for a wide range of temperatures $60 < T < 280$ K. Pure polyaniline showed a $\nu \approx -0.51$ slope, associated with a quasi-one-dimensional $n \approx 0.9$ hopping process. However, PANI-GOQD- X showed $\nu \approx -0.26$ and -0.23 slopes for $X = 1$ and 3 , suggesting an increase of the hopping dimension with respect to pure PANI with $n \approx 2.9$ and 3.3 , respectively. This is probably suggesting that the addition of low amounts of GOQD leads to the modification of the

hopping process due to the interaction of polyaniline charge carriers with the π electron density of GOQD. Essentially, we propose that polyaniline aromatic rings are probably interacting via π – π stacking with GOQD, favoring the redistribution of the charge carriers through the π electron density of GOQD. This effect not only explains the change in the charge carrier pathway dimensionality but also explains the enhancement on the resistivity with increasing GOQD additions. However, higher GOQD loadings ($X = 5$) showed $\nu \approx -0.43$, in relation with a decrease of the fractal hopping dimension with $n \approx 1.3$. The decrease in the electrical transport dimensionality could be associated with the increase in the degree of order of polyaniline chains observed for high amount of GOQD addition. It is important to remark that fractal dimension estimated using small-angle X-ray diffraction was practically unchanged from $D \approx 1.5$ – 2.0 for all different GOQD additions, suggesting that the microstructural pattern of these nanocomposites was not drastically modified by the presence of low amounts of graphene quantum dots. However, the electrical transport dimensionality increases from 1D to 3D when a critical GOQD addition ($X = 3$) is reached. In order to explain this behavior, it is well-accepted that the hopping transport in pure polyaniline can occur along each polyaniline chain or through cross-linked chain clusters.³¹ Based on this description, the expected transport dimensionality for pure polyaniline should be quasi-one-dimensional, as it was estimated using the reduced activation energy plot analysis. However, the π – π stacking interaction between GOQD and polyaniline chains can also promote the mediation in the electrical transport favoring the possibility of hopping between adjacent polyaniline chains leading to the modification of the charge carrier pathway. This effect could be explaining the increase in the electrical transport dimensionality although no drastic modification in the fractal dimension was observed using SAXS technique.

4. CONCLUSIONS

We report the preparation of polyaniline–graphene oxide quantum dots nanocomposites, a detailed study of their structure and microstructure by means of atomic force microscopy, small-angle X-ray scattering, and X-ray diffraction and a thorough electrical characterization. The addition of graphene oxide quantum dots essentially leads to the enhancement in the degree of order of polyaniline fibers and fractal dimension from intermediate one- to quasi-two-dimensional values. In addition, confocal Raman spectroscopy analysis showed that an increase of graphene oxide quantum dots leads to a decrease in the polyaniline polaron population in agreement with the decrease in the conductivity. In all nanocomposites, the electrical transport followed a typical Arrhenius behavior at relatively high temperatures and a broad transition with logarithmic dependence of the activation energy at intermediate temperatures. However, the addition of graphene oxide quantum dots showed an increase in the transport dimensionality from 1D to 3D for low amounts of graphene oxide quantum dot addition. The tuning of the electric transport dimensionality could be of interest for novel electronic device applications.

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Notes

The authors declare no competing financial interest.

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