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Citation: *J. Appl. Phys.* **121**, 045109 (2017); doi: 10.1063/1.4974970

View online: <http://dx.doi.org/10.1063/1.4974970>

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Effect of graphene-oxide on the microstructure and charge carrier transport of polyaniline nanocomposites under low applied electric fields

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(Received 4 November 2016; accepted 15 January 2017; published online 30 January 2017)

We report a study on the preparation and characterization of polyaniline-graphene oxide (PANI-GO-X) nanocomposites focusing in the study of its structure, microstructure, and correlations with electrical transport properties under low applied electric fields. X-ray diffraction analysis showed evidence of graphene oxide (GO) blending between polyaniline fibers, and according to small angle X-ray scattering, the fractal dimensionality was quasi-one dimensional for all nanocomposites. Confocal Raman spectroscopy revealed that the addition of GO leads to a notorious decrease of the polaron population of polyaniline. A significant increase in resistivity was observed for PANI-GO-X nanocomposites with respect to pure polyaniline, in agreement with the decrease in the polaron population. The electrical transport mechanism could be explained by an Arrhenius behavior at high temperatures ($T > 255$ K) and a broad transition with a logarithmic dependence of the activation energy with temperature for the low temperature regime ($T < 255$ K). Additionally, an increase in the hopping transport dimensionality from quasi-1D to quasi-3D was observed for $X = 7\%$ GO nanocomposites. The transport properties, studied after the polarization using low applied electric fields, revealed the modification of the electrical transport at low temperatures. In addition, the electrical transport of PANI-GO-X nanocomposites followed a typical $\ln(\sigma)$ vs $E^{1/2}$ Poole-Frenkel type dependence in the presence of low applied electric fields. At low temperatures, $X = 7\%$ GO nanocomposites showed a notorious increase in the Poole-Frenkel slope at low applied electric fields with respect to pure polyaniline. The enhancement on the electric response using low applied electric fields ($E \sim 2$ V/cm) could be of great interest for the development of new organic electronic devices. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4974970>]

I. INTRODUCTION

In recent years, the preparation and characterization of conductive polymer-based flexible devices for electromagnetic sensing,^{1,2} energy conversion,³ and storage⁴ applications have been of great interest. One of the most promising materials for these organic electronic devices is polyaniline (PANI) due to its good electric conductivity ($\sigma \sim 10^1$ S/cm) and high dielectric constant ($\epsilon' \sim 10^2$ – 10^3).⁵ Moreover, the preparation of nanocomposites with PANI and carbon nanotubes⁶ or graphene⁷ has yielded excellent electrical properties. In addition, there are several experimental and theoretical studies, regarding the research on the polyaniline nanocomposite electrical transport mechanism.^{8,9} It is well accepted that the polyaniline electrical transport mechanism is mostly based on the hopping process of charge carriers,⁵ but the effect of carbon-based nanostructure addition on it is still under discussion. In addition, there are several studies regarding the effects of magnetic fields on the electrical response of this nanocomposites^{10,11} but very few reports studying the effects of external electric fields on their electrical transport mechanism.¹² Nevertheless, there are theoretical approaches describing the electric field effects on the

electrical conductivity of disordered conductive polymers¹³ but still very few correlations with experimental studies.^{14–16}

In the present paper, we report on the structure, microstructure, and electrical transport properties of polyaniline-graphene oxide (PANI-GO-X) nanocomposites. In addition, we also report on the electrical transport mechanism in the presence of low applied electric fields. PANI-GO-X nanocomposites were characterized using X-ray powder diffraction (XRD), and small angle X-ray scattering (SAXS) was used in order to study their structure, microstructure, and fractal dimensionality. Confocal Raman imaging and Raman spectroscopy were performed to study the microstructure and the presence of polyaniline polarons in these nanocomposites. Additionally, we present correlations between microstructural characterization and the electrical transport mechanism for these conductive polymer nanocomposite systems. Finally, we show the electrical transport properties of these PANI-GO-X nanocomposites polarized in the presence of low applied electric fields.

II. MATERIALS AND METHODS

A. Preparation of graphene oxide (GO)

Graphene oxide (GO) was prepared using the Hummer's modified method.¹⁷ In our experiment, we added 100 mL of concentrated sulfuric acid (H_2SO_4) to 2 g of graphite powder under magnetic stirring at $\sim 5^\circ C$ for 30 min. Then, 8 g of

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potassium permanganate (KMnO_4) were added under stirring followed by the addition of 100 mL of distilled water. After an hour, 60 mL of hydrogen peroxide (H_2O_2 , 30%) were added and the precipitate was washed, first using hydrochloric acid (HCl , 5%) and then with distilled water until $\text{pH} = 7$.

B. Preparation of polyaniline graphene oxide nanocomposites (PANI-GO-X)

GO aqueous solution was dried at 100°C for several hours to remove residual water and re-suspended in 10 mL of tetrahydrofuran. PANI emeraldine salt (PANI-DBSA- H_2SO_4) with average Mw $\sim 15\,000$ provided by Sigma-Aldrich was dissolved separately in 10 mL of tetrahydrofuran and then added to the GO tetrahydrofuran suspension. PANI and GO tetrahydrofuran mixed suspension was vigorously stirred and heated at $T = 70^\circ\text{C}$ for several hours until dryness to remove residual solvent. The PANI-GO dried powder was then grinded and compressed at 50 kN for 10 min to form pellets with a $\sim 800\,\mu\text{m}$ thickness and 12 mm diameter. In this report, nanocomposites were studied with the following GO weight fraction additions: 0, 1, 5, 7, and 10%w/w, named as PANI-GO-X with $X=0, 1, 5, 7$, and 10, respectively.

C. Characterization

PANI-GO-X nanocomposites were studied by X-ray diffraction (XRD) using a Rigaku Ultima IV diffractometer working in Bragg-Brentano configuration with $\text{CuK}\alpha$ radiation in the $2\theta = 5^\circ\text{--}45^\circ$ range using 2θ steps of 0.02° with a 5 s integration time per step. Grazing incidence small angle X-ray scattering (GI-SAXS) was performed using a Rigaku Ultima IV diffraction system working in parallel beam configuration with $\text{CuK}\alpha$ radiation in the $q = 0.01\text{--}0.50\,\text{\AA}^{-1}$ range and fixed incident angle at 0.2° with respect to the critical angle. Confocal Raman images and Raman spectra were obtained using WITec Alpha 300-RA. Raman spectra for PANI-GO-X nanocomposites were collected using a 532 nm laser wavelength and the laser power was adjusted at $\sim 3\,\text{mW}$ to avoid polyaniline decomposition. For each case, a set of 20 spectra with 0.2 s integration time were averaged. Additionally, confocal Raman images were obtained for a $20 \times 20\,\mu\text{m}^2$ total area with a resolution of $\sim 265 \times 265\,\text{nm}^2$ per pixel by collecting the total amount of 5625 Raman spectra. 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. Resistivity versus temperature for PANI-GO-X with $X=0, 1, 5, 7$, and 10 was measured from the heating cycles for zero electric field cooling (ZEFC) (unpolarized) and electric field cooling (polarized) in the absence and presence of a perpendicularly applied electric field ($E = 2.5\,\text{V/cm}$), respectively. Resistivity versus applied electric field was also measured for the polarized samples stabilized at the lowest temperature ($T = 12\,\text{K}$) for the $E = 0\text{--}2.5\,\text{V/cm}$ electric field range.

III. RESULTS AND DISCUSSION

X-ray powder diffraction (XRD) patterns for PANI-GO-X nanocomposites are displayed in Fig. 1. The $X=0$ sample showed a typical XRD profile for pure polyaniline in its emeraldine salt conformation, which is composed of two broad peaks at $2\theta = 15.4^\circ$ and 19.8° and a sharper peak at $2\theta = 25.2^\circ$, with associated mean coherence distances $d \sim 6.0, 4.4$, and $3.5\,\text{\AA}$, respectively.¹⁸ In addition, the appearance of two broad peaks at $2\theta = 8.0$ and 9.3° with associated spacings of $d \sim 11.1$ and $9.5\,\text{\AA}$ was observed for PANI-GO-X, and their relative intensity increased with increasing GO additions. XRD analysis for pure GO showed a broad peak at $2\theta = 10.8^\circ$ with an associated spacing of $d \sim 8.2\,\text{\AA}$, as shown in Fig. 1-inset. The 2θ shift of the GO peak observed for PANI-GO-X nanocomposites suggests an increase in the mean d -spacing between GO planes due to the blending and location of PANI chains between GO planes. However, as the increase in the GO spacing is not drastic, it is also possible that this increase can be also partially explained by the $\pi - \pi$ stacking interaction between GO and PANI aromatic rings.

Grazing incidence small angle X-ray scattering (GI-SAXS) curves for PANI-GO-X are displayed in Fig. 2. In the low q -region, a well-defined bump was observed for all samples, suggesting the presence of nanometric clusters ascribed to the presence of nanometric polyaniline nodules. In the high- q region, SAXS curves can be fitted with a $I(q) \sim q^{-P}$ power law, with P related to the sample fractal dimension (D) following $D = P + 1$ for $P = 0\text{--}2$.¹⁹ SAXS analyses in the high- q region displayed in Fig. 2 inset showed a $\ln[I(q)]$ vs $\ln(q)$ linear dependence with very small slopes ($P \sim -0.07$ to -0.14) suggesting a quasi-1D fractal dimension for all PANI-GO-X nanocomposites, as summarized in Table I.

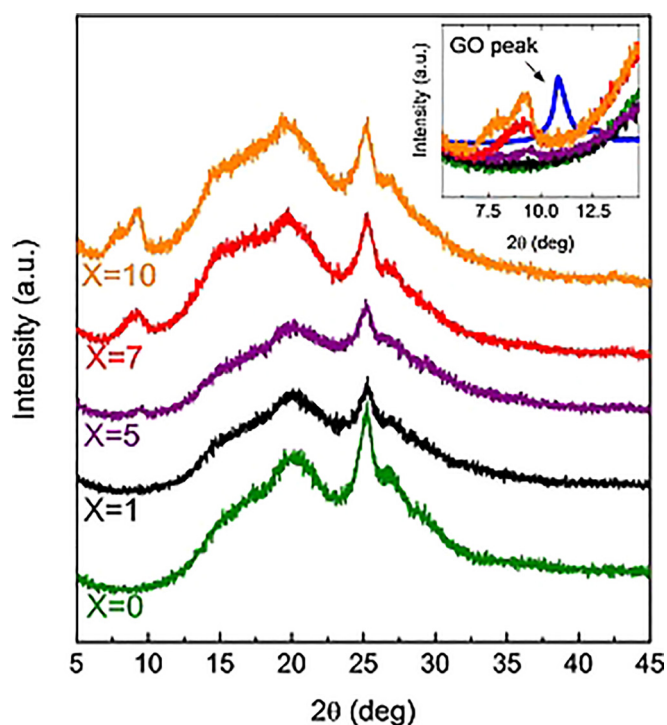


FIG. 1. XRD patterns for PANI-GO-X with $X=0, 1, 5, 7$, and 10. The inset shows the 2θ shift of the GO peak in PANI-GO-X nanocomposites.

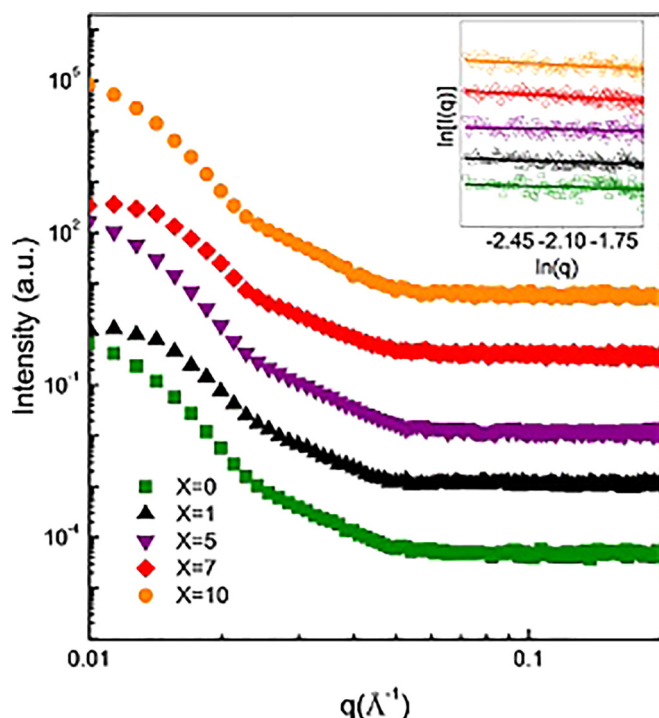


FIG. 2. GI-SAXS analysis for PANI-GO-X with $X=0, 1, 5, 7$, and 10 . The $\ln[I(q)]$ vs $\ln(q)$ plots and linear fit in the high- q region are shown in the inset.

Only a slight increase in the fractal dimension from $D \sim 1.0$ to 1.2 was observed with increasing GO additions. This suggests that the addition of small amounts of the quasi-two dimensional 2D GO only leads to a slight increase of the quasi-1D fractal dimension for PANI-GO-X nanocomposites with increasing X .

Raman spectra for PANI-GO-X and the most relevant vibrational modes assignments are shown in Fig. 3. Raman spectra for pure GO showed two typical broad peaks at ~ 1355 and 1603 cm^{-1} , ascribed to D and G modes, respectively. On the other hand, Raman spectra for pure PANI showed peaks at $\sim 576, 830, 1158\text{--}1196, 1260, 1334, 1507, 1591$, and 1623 cm^{-1} , ascribed to oop(C-N-C-H) out-of-plane deformation, wag(C-H) wagging, $\delta(\text{C-H})$ bending,

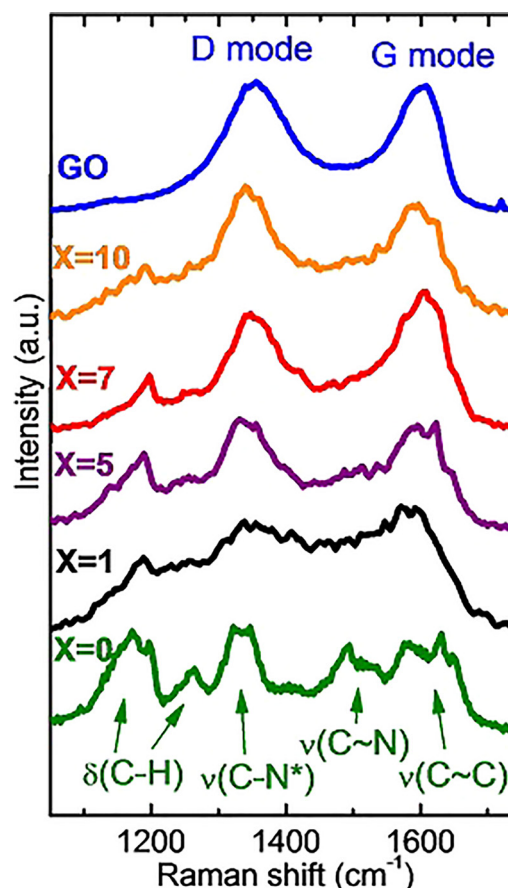


FIG. 3. Raman spectra for GO and PANI-GO-X with $X=0, 1, 5, 7$, and 10 .

$\nu(\text{C-N})$ symmetric stretching, $\nu(\text{C} \sim \text{N})$ asymmetric stretching, rock(C-H) rocking, $\delta(\text{N-H})$ bending, and $\nu(\text{C}=\text{C})$ stretching modes, respectively.²⁰ Raman spectra for PANI-GO-X nanocomposites showed an increase in the relative intensity of peaks at ~ 1344 and 1599 cm^{-1} , as a direct consequence of GO increasing concentration. Confocal Raman images shown in Fig. 4(a) were obtained by filtering the PANI $\delta(\text{C-H})$ bending mode at $\sim 1196 \text{ cm}^{-1}$ and GO G mode at $\sim 1603 \text{ cm}^{-1}$, in order to define PANI-rich (green) and GO-rich (blue) zones, respectively. The presence of PANI-rich and GO-rich zones in Fig. 4(a) suggests that GO and PANI are homogeneously blended in the nanocomposites. Raman spectra for PANI-rich and GO-rich zones in the nanocomposites are shown in Fig. 4(b). It is observed that the peak ascribed to the polaron $\text{C} \sim \text{N}^{+*}$ stretching mode for PANI-GO-X showed a remarkable decrease in its relative intensity with GO additions, as shown in Fig. 4(b). The decrease is especially noticeable for low amounts GO additions ($X=1$ and 5), when the GO D peak, which appears at the same frequency, has lower relative intensity due to GO lower concentration. It has been theoretically²⁰ and experimentally evidenced^{21,22} that the C-N asymmetric stretching mode at $\sim 1334 \text{ cm}^{-1}$ is a sharp peak with a high relative intensity in the polaron configuration and declines its intensity in the bipolaron configuration. This reveals that the presence of GO essentially leads to a declining of polyaniline polaron population probably due to polyaniline charge carrier interactions with GO π electron density.

TABLE I. XRD and SAXS analyses for PANI-GO-X with $X=0, 1, 5, 7$, and 10 .^a

	$X=0$	$X=1$	$X=5$	$X=7$	$X=10$	GO
d_1 (PANI) (nm)	0.354(6)	0.353(9)	0.354(9)	0.353(6)	0.354(7)	...
d_2 (PANI) (nm)	0.444(33)	0.447(38)	0.446(49)	0.446(34)	0.451(38)	...
d_3 (PANI) (nm)	0.56(10)	0.57(11)	0.56(14)	0.57(8)	0.58(9)	...
d_4 (GO) (nm)	...	...	0.94(18)	0.98(13)	0.96(8)	0.812(9)
P	0.07(3)	0.08(2)	0.06(2)	0.14(2)	0.12(2)	...
D	1.07(3)	1.08(2)	1.06(2)	1.14(2)	1.12(2)	...

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

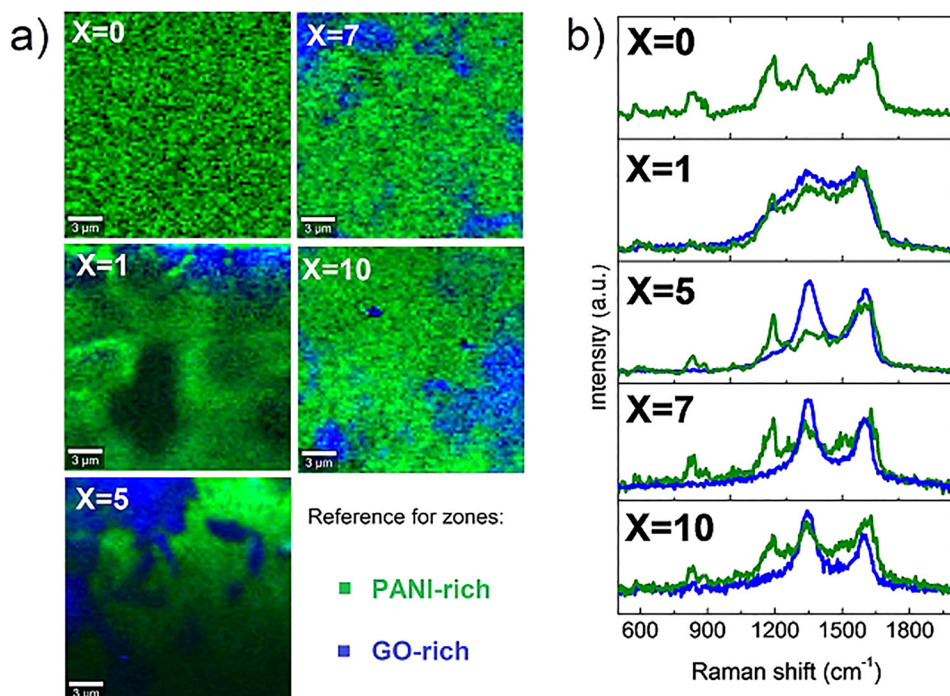


FIG. 4. (a) MicroRaman images and (b) Raman spectra at selected area for PANI-GO-X with X = 0, 1, 5, 7, and 10. PANI-rich and GO-rich zones are shown in green and blue, respectively.

Resistivity versus temperature curves measured using the heating cycle with previous zero electric field (ZEFC) and electric field (EFC) cooling for PANI-GO-X nanocomposites are shown in Fig. 5. In all cases, a typical exponential increase of resistivity with decreasing temperature was observed, in agreement with a semiconductor behavior. In all cases, an increase in the resistivity with increasing GO additions was observed for the entire temperature regime

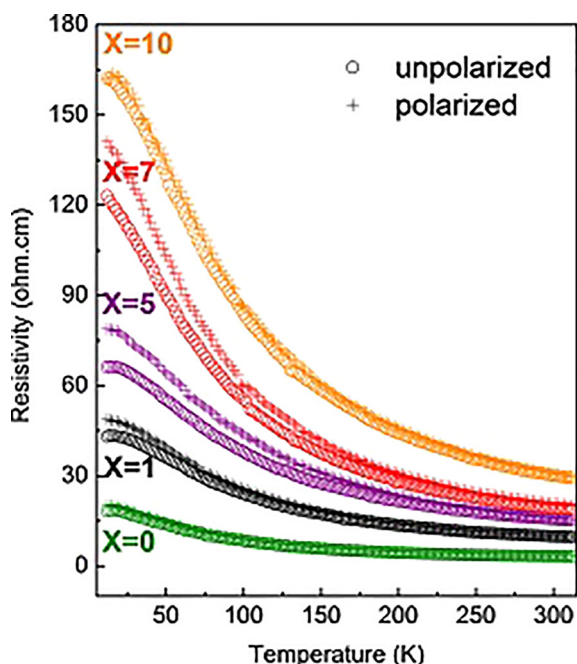


FIG. 5. Resistivity versus temperature heating cycles for unpolarized (circles) and polarized (crosses) PANI-GO-X with X = 0, 1, 5, 7, and 10 during zero electric field and electric field cooling. The electric field cooling was performed in the presence of a low applied electric field ($E = 2.5$ V/cm) and in both cases, the heating cycles were measured in the absence of external applied electric field.

analyzed, in agreement with the decrease of polaron population observed by the Raman analysis. However, a splitting of the resistivity was observed at low temperatures when comparing ZEFC and EFC curves. Pure PANI showed no appreciable polarization effect at low applied electric fields but the effect is especially appreciable for 5% and 7% GO loadings. The bifurcation of zero electric and electric field curves is a typical consequence of the formation inhomogeneous metastable states, as recently reported for polyaniline nanocomposites.¹² However, for X = 10 the polarization effects decrease. The electrical transport of these PANI-GO-X nanocomposites can be described by the Arrhenius law, in the higher temperature regime ($T \sim 300$ – 255 K), which can be expressed by the following equation:

$$\sigma(T) \sim \exp\left(-\frac{E_{a0}}{k_B T}\right)$$

for which σ is the dc conductivity, E_{a0} is the activation energy, and k_B is the Boltzmann constant. Arrhenius plots $\ln(\sigma)$ vs. T^{-1} for PANI-GO-X nanocomposites are shown in Fig. 6. In all cases, the linearity behavior was observed for the high temperature regime ($T > 255$ K) and the corresponding activation energies for zero electric field ($E_{a0,ZEFC}$) and electric field ($E_{a0,EFC}$) cooling obtained from the slope are summarized in Table II. A slight increase in the high temperature activation energy was observed from $E_{a0} \sim 17$ to 22 meV with increasing GO additions but no significant variations (~ 1 meV) were observed for both ZEFC and EFC curves, as shown in Table II.

At intermediate temperatures, the Arrhenius plots usually show an apartment from linearity, which can be described by the Larkin and Khmel'nitskii prediction of a logarithmic dependence of the activation energy for disordered systems with large localization length

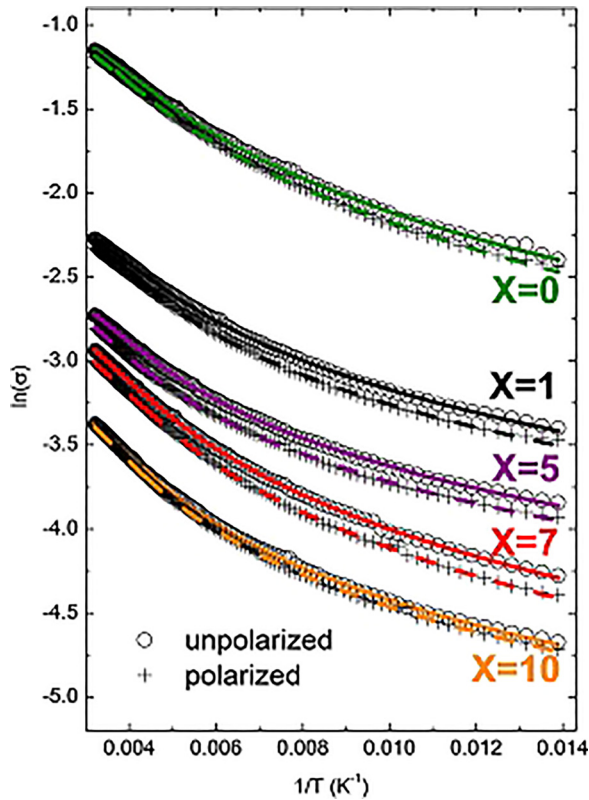


FIG. 6. $\ln(\sigma)$ vs T^{-1} plots for unpolarized (circles) and polarized (crosses) PANI-GO-X with $X=0, 1, 5, 7$, and 10 . Linear and logarithmic fits for unpolarized and polarized samples are represented with solid and dashed lines, respectively.

$$\sigma(T) \sim \exp\left(-\frac{E_{a1}}{k_B T} [\ln(\alpha T - \beta)]\right)$$

with α and β depend on the localization length, hopping length, electric field, and pellet thickness.²³ PANI-GO-X with $X=0, 1, 5, 7$, and 10 showed excellent fits using the activation energy logarithmic dependence with temperature for the $T \sim 255\text{--}70\text{ K}$ regime. Based on this model, the length of the hop (x_0) should be equal to the localization length (L_c) at the transition temperature $T \sim 255\text{ K}$ and increases in relation to L_c with decreasing temperatures.

The reduced activation energy (W), defined as $W = \partial \ln(\sigma) / \partial \ln(T)$, is generally used to obtain the electric transport dimensionality (n) by estimating the slope of the $\log W$ vs. $\log T$ plots, as shown for PANI-GO-X in Fig. 7. The electrical transport dimensionality (n) extracted from the slope (ν) of the $\log W$ vs. $\log T$ following $n = (1/\nu) - 1$ ²⁴ is shown in Table III. The transport dimensionality (n) showed a drastic increase with increasing GO additions and a slight

TABLE II. Arrhenius activation energy plots analysis for zero electric field and electric field cooling of PANI-GO-X with $X=0, 1, 5, 7$, and 10 .^a

	$X=0$	$X=1$	$X=5$	$X=7$	$X=10$
$E_{a0, \text{ZEFC}}$ (meV)	16.6(2)	16.4(2)	17.5(1)	20.3(2)	21.4(2)
$E_{a0, \text{EFC}}$ (meV)	17.3(2)	17.0(1)	19.2(1)	20.8(1)	22.1(1)

^aArrhenius activation energies E_{a0} were extracted from the $\ln(\sigma)$ vs T^{-1} linear fit in the high temperature regime ($T \sim 310\text{--}255\text{ K}$).

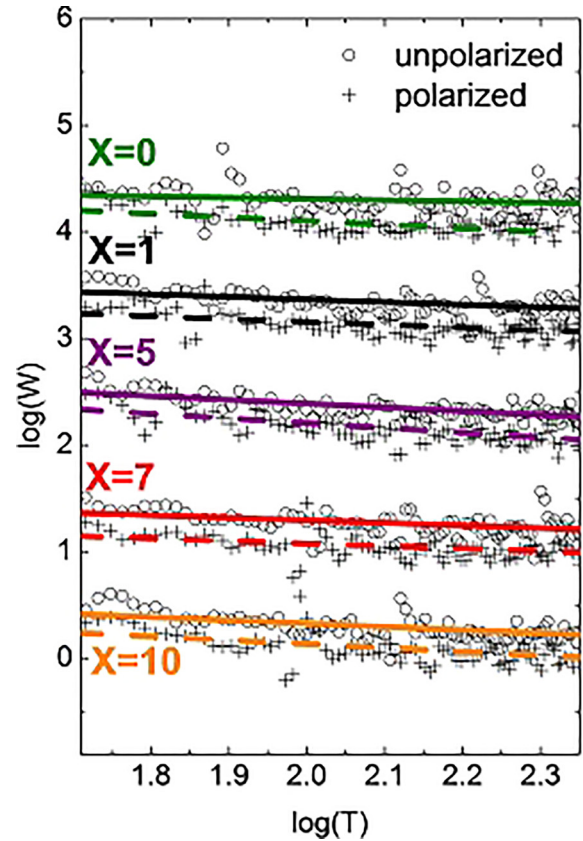


FIG. 7. Reduced activation energy plots $\log W$ vs $\log T$ for unpolarized (circles) and polarized (crosses) PANI-GO-X with $X=0, 1, 5, 7$, and 10 . Linear fits for unpolarized and polarized samples are represented with solid and dashed lines, respectively.

decrease for polarized samples at low applied electric field. Pure PANI transport dimensionality was $n \sim 1.3$, as expected for a quasi-one dimensional polymer chain. However, a drastic increase in the transport dimensionality was observed for low amounts of GO addition ($X=7$) with $n \sim 3$. This evidences the GO participation in the electric transport mechanism probably through the interaction of π electronic density with the charge carriers leading to a modification of the transport pathway. At higher GO additions ($X=10$), the transport dimensionality decreases with $n \sim 1.7$ probably suggesting that higher GO concentrations lead to a quasi-two dimensional charge carrier pathway.

The electric field (E) dependence of the electric conductivity (σ) for disordered semiconductors can be described by the Poole-Frenkel equation

TABLE III. Reduced activation energy and Poole-Frenkel plots analyses for zero electric field and electric field cooling of PANI-GO-X with $X=0, 1, 5, 7$, and 10 .^a

	$X=0$	$X=1$	$X=5$	$X=7$	$X=10$
n_{ZEFC}	~ 1.2	~ 3.1	~ 1.8	~ 3.2	~ 1.7
n_{EFC}	~ 1.9	~ 2.9	~ 1.3	~ 3.2	~ 1.3
γ (cm/V) ^{1/2}	~ 0	~ 0.012	~ 0.039	~ 0.063	~ 0.012

^aThe transport dimensionality factor (n) was calculated from the $\log W$ vs $\log T$ slope (ν) following $n = (1/\nu) - 1$. The Poole-Frenkel slope (γ) was extracted from the $\ln(\sigma)$ vs $E^{1/2}$ linear fit.

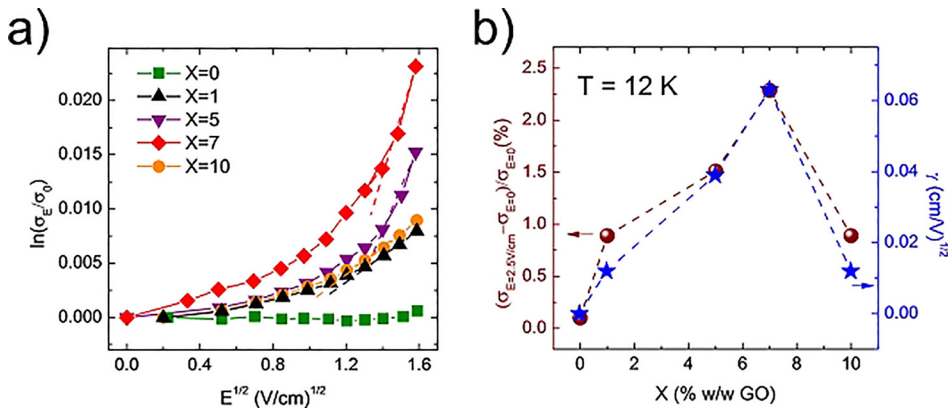


FIG. 8. (a) Poole-Frenkel plots and (b) Poole-Frenkel slopes (γ) dependence with X at T = 12 K for PANI-GO-X with X = 0, 1, 5, 7, and 10.

$$\sigma(E, T) \sim \exp\left(\frac{\gamma E^{1/2}}{k_B T}\right),$$

where E is the electric field, γ is a temperature dependent constant related to the field activation, and k_B is the Boltzmann constant. This equation indicates that the increase of the applied electric field leads to a decrease of the global activation energy of the electrical transport. Basically, the hopping charge carriers gets accelerated under the application of an external electric field (E), gaining an electrostatic energy (U) equal to $U = qEa$, where q is the charge and a is the charge inter-distance.¹⁶

Recently, it has been theoretically reported that the Poole-Frenkel law can be used to describe well the large carrier concentration transport regime.¹³ However, at these large carrier concentrations, the Coulombic potentials may be considered as non-overlapping to affirm that the Poole-Frenkel behavior obeys a $\sigma \sim \exp(E^{1/2})$ dependence.²⁵ The electrical conductivity dependence with the applied electric fields for PANI-GO-X nanocomposites at a fixed temperature ($T = 12$ K), represented using the $\ln(\sigma)$ vs. $E^{1/2}$ Poole-Frenkel plots, is shown in Fig. 8(a). Pure PANI conductivity showed almost no variations with these low applied electric fields ($E < 2.5$ V/cm), suggesting that no significant modification of the global activation energy of the electrical transport occurs for unloaded PANI. However, the addition of low amounts of GO showed an increase of the electrical conductivity for low applied electric fields. Moreover, X = 5 and 7 showed a linear increase in conductivity above a critical applied electric field ($E \sim 1.5$ V/cm), suggesting that the presence of GO drastically modifies the global activation energy of the electrical transport in these PANI-GO-X nanocomposites. The Poole-Frenkel slopes (γ) are also known as the activation field parameter and can be estimated from the linear fit of $\ln(\sigma)$ vs $E^{1/2}$ plots, as summarized for PANI-GO-X in Table III. A drastic increase of the Poole-Frenkel slope (γ) was observed with increasing GO additions showing a maximum at X = 7, with $\gamma \sim 0, 0.012, 0.039, 0.063$, and 0.012 (cm/V) $^{1/2}$ for X = 0, 1, 5, 7, and 10, respectively. In addition, the difference between the conductivity at zero ($\sigma_{E=0}$) and the maximum applied electric field ($\sigma_{E=2.5\text{V/cm}}$) followed the same trend for all GO loadings, as shown in Fig. 8(b). The increase in the Poole-Frenkel slopes (γ) with increasing GO additions is in relation to a large carrier

concentration associated with the Poole-Frenkel effect. The increase of γ is probably ascribed to the increase in the charge inter-distance caused by the GO addition, which leads to both the declining on the mobility and the increase of the electrostatic energy between charge carriers. On the contrary, the increasing mobility usually leads to a decrease of γ , as recently observed for PANI-Ag nanocomposites.²⁶ However, in our PANI-GO-X nanocomposites, the addition of a critical amount of GO ($\sim 7\%$) showed an enhancement of γ suggesting that this particular GO loading maximizes the electric transport under low applied electric fields. One possible explanation to this behavior could be related to the modification of the electrical transport dimensionality. The increase in the transport dimensionality from quasi-1D to quasi-3D for 7% GO loading is probably associated with the optimization of $\pi - \pi$ stacking interactions between GO and PANI aromatic rings, leading to the modification of the charge carrier pathway through these PANI-GO-X nanocomposites. In this scenario, it is possible that the modification of the charge carrier pathway from quasi-1D to quasi-3D is also related to the increase of the electrostatic energy and thus of the field activation parameter (γ).

IV. CONCLUSIONS

In this report, we showed the preparation and characterization of polyaniline-graphene oxide (PANI-GO-X) nanocomposites focusing in the study of its structure, microstructure, and correlations with electrical transport properties under low applied electric fields. Evidence of GO blending between polyaniline fibers was observed using XRD analysis, and no drastic modifications of a quasi-one fractal dimensionality for all nanocomposites was determined using the SAXS technique. Moreover, the addition of GO leads to a notorious decrease of the polaron population of polyaniline, as observed using μ Raman spectroscopy. In agreement with the previous evidence, a significant increase in resistivity was observed for PANI-GO-X nanocomposites with respect to pure polyaniline. The electrical transport mechanism followed an Arrhenius behavior at high temperatures ($T > 255$ K) and a broad transition with a logarithmic dependence of the activation energy with temperature for the low temperature regime ($T < 255$ K). A remarkable increase in the hopping transport dimensionality from ~ 1 D to ~ 3 D was observed for 7% GO nanocomposites suggesting a notorious modification of the charge carrier

pathway with low amounts of GO. In addition, the electrical transport of PANI-GO-X nanocomposites followed a typical $\ln(\sigma)$ vs $E^{1/2}$ Poole-Frenkel type dependence in the presence of low applied electric fields with a maximum in the Poole-Frenkel slope (γ) for 7% GO nanocomposites. As shown here, the inclusion of low percentages of GO (<10%) in the PANI matrix affects significantly the transport properties in comparison to the pristine polymer. The enhancement on the electrical response using low applied electric fields could be of great interest in the development of new organic electronic devices.

ACKNOWLEDGMENTS

The authors wish to thank the Uruguayan funding institutions CSIC, ANII, and PEDECIBA. We would like to thank financial support of ANII-FCE-3-2013-1-100623 and EQC-X-2012-1-14 research projects.

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