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Composites of Poly(3,4-ethylenedioxythiophene) and $CoFe_2O_4$ Nanoparticles: Composition Influence on Structural, Electrical, and Magnetic Properties

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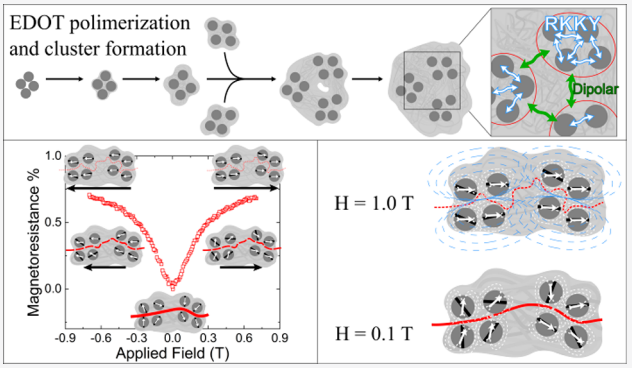
ABSTRACT: Composites of magnetic $CoFe_2O_4$ nanoparticles (MNP) in a poly(3,4-ethylenedioxythiophene) matrix at different ratios have been synthesized. Composites were characterized by electron microscopy, X-ray diffraction, thermal analysis, electrical conductivity, magnetization, and magnetoresistance studies. In the composites the MNP appear clustered, with an interparticle distance essentially constant, but where two regimes are distinguished for cluster separation: for high MNP concentrations an intercluster separation similar to the interparticle distance is found, while for low MNP contents the distance between clusters is larger than the interparticle separation. The electrical conductivity increases with polymer content, but being always far lower than general effective medium theory expectations. This indicates that the effect of MNP effect on polymer conduction is probably related to the generation of mechanical stress both by introducing additional scattering centers and by producing different arrangement of the polymer chains, compared with the pure PEDOT. The magnetization studies reveal the existence of the RKKY interaction, which couples ferromagnetically the MNP located in a cluster, while the dipolar interaction dominates the interaction between clusters. Magnetoresistance was studied for these composites, with a maximum value close to 0.7% at 0.7 T for the lowest polymer content. The magnetoresistance correlates very well with the reversible part of the magnetization, indicating that its possible origin should be associated with polymer mechanical deformation due to the magnetic-field-induced rotation of the MNP.



INTRODUCTION

Composite materials based on conducting polymers and magnetic nanoparticles (MNP) have received much attention in the past years.[1−11] Conducting polymers, on the one hand, have interesting chemical, conducting, mechanical, and optical properties leading to a high number of proposed applications.[12−15] In particular, poly(3,4-ethylenedioxythiophene (PEDOT) is highly interesting because of its excellent environmental stability,[16] high electrical conductivity,[17] and transparency in the doped state.[18] On the other hand, MNP are also highly interesting materials due to their potential applications in different fields.[19,20] In particular, spinel ferrite nanoparticles have been intensively investigated, and among them, cobalt ferrite ($CoFe_2O_4$) is especially interesting because it is a hard material from the magnetic point of view and has moderate saturation magnetization, exhibiting also excellent stability.[21,22] Also, it has promising application for microelectronic devices, actuators, and transducers. Thus, by combination of conducting polymers and MNP, it is possible to obtain materials with high magnetic susceptibilities and high electrical conductivities, giving rise to applications in nonlinear optics, electromagnetic interference shielding, microwave absorption, electrochemical supercapacitors, ion adsorption, and electrocatalysis, among others.[8,11,23−28] All these applications underline the importance of the study of these composites from an applied point of view, besides the fundamental interest. In particular, there are few reports concerning composites based on PEDOT and MNP, which studies include microwave absorption behavior,[28] adsorption of heavy metal ions,[29] and catalytic performance.[25] Another interesting property shown by conducting polymers, including PEDOT, is the magnetoresistance effect (OMAR),[30−34] mainly associated with the spin correlations between different carriers, while the standard magnetoresistance (MR) refers to the phenomenon in which the electrical resistance of a material

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changes when an external magnetic field is applied to it. This latter effect was also studied in MNP, in particular magnetite[35] and ferrites.[36,37] It is proposed that materials that show MR could be applied in spintronics, electronics, computer memory, storage technology, and magnetoresistance sensors.[34,38−40] For these reasons, there are several challenges in the design of novel and suitable magnetic materials that show an improved magnetoresistance effect. Within these materials, composites based on conducting polymers and MNP are attractive candidates for this end,[41,42] although to the present their magnetoresistance effect has not been study deeply. Is the MR effect related to the local magnetic field generated by the MNP? Does the metallic nature of the polymeric matrix affect the magnetic interactions and then influence the MR effect? How can the MR be maximized? To answer these questions, it is necessary to perform an exhaustive and complete physicochemical characterization in order to have tools allowing to synthesize a material with the desired properties, this is to say, to tune the physicochemical properties through the synthetic route employed.[43,44] To the best of our knowledge, there are relatively few reports that show the dependence of the final properties of PEDOT-based composites (such as electrical conductivity, magnetic properties, and morphology) on the conducting polymer:MNP molar ratio in the composites.[3,41,45] In a recent study,[46] the thickness of the polymer shell of core−shell magnetite−PEDOT microspheres was tuned by varying the magnetite:monomer molar ratio. Moreover, to have a better understanding of the influence of the composition on the final properties, it is important to study the magnetic interactions between the different components in the composites. To the present, and to the best of our knowledge, there are no reports concerning the type and magnitude of the magnetic interactions in composites based on PEDOT conducting polymer and $CoFe_2O_4$ nanoparticles. The change in the type and magnitude of the magnetic interactions with the composite composition is a fundamental study to gain insight, also, into the potential application of these materials in the magnetoresistance field.

In this work, composites based on PEDOT and MNP of $CoFe_2O_4$ were chemically synthesized by varying the EDOT:MNP molar ratio in the feed solution to obtain materials with different compositions. Morphology, crystallinity, electrical conductivity, magnetoresistance, and magnetic properties, focusing on the type and magnitude of the interactions, were thoroughly studied and analyzed to understand their correlations with the overall electric and magnetic properties.

MATERIALS AND METHODS

AR grade chemicals, supplied by Sigma-Aldrich, and high purity water (18 MΩ cm) from a Milli-Q system were employed throughout. Ethylenedioxythiophene (EDOT) was used as received.

Synthesis of Cobalt Ferrite Nanoparticles. The synthesis of $CoFe_2O_4$ nanoparticles was performed by following Antonel et al.[47] Briefly, 22.25 mL of a solution containing 0.450 M $FeCl_3{\cdot}6H_2O$ and 0.225 M $CoCl_2{\cdot}6H_2O$ (2:1 Fe(III)−Co(II) molar ratio), in 0.4 M HCl, was added dropwise to 200 mL of 1.5 M NaOH under constant and high speed mechanical stirring. The synthesis temperature was set at 80 °C by using a water-jacketed reaction vessel with a circulating thermostatic bath. Dark brown $CoFe_2O_4$ nanoparticles precipitated immediately after the first drops of the Fe(III)−Co(II) solution. The temperature of synthesis and the high-speed mechanical stirring were kept constant during the addition of the cationic solution. After the addition of this solution, the reaction media was maintained at 80 °C, at high-speed stirring, for 2 h. The $CoFe_2O_4$ nanoparticles were separated by centrifugation at 12000*g* for 20 min at room temperature. The pellet was washed with Milli-Q water, repeating the cycles of washing−centrifugation until neutral pH of the supernatant was reached (about 10 times). Finally, the $CoFe_2O_4$ nanoparticles were dried by using a vacuum oven at 40 °C for 24 h.

Synthesis of $CoFe_2O_4$−PEDOT Composites and PEDOT. $CoFe_2O_4$−PEDOT composites were synthesized by following Ohlan et al.,[48] with some modifications. First, $CoFe_2O_4$ nanoparticles were added to a 0.1 M dodecylbenzenesulfonic acid (DBSA) solution (used as both protecting agent and acid media) in a $CoFe_2O_4$:DBSA molar ratio of 0.33. To efficiently disperse the MNP and to allow DBSA adsorption onto them, strong mechanical stirring and ultrasound treatment were applied for 30 min. This was performed by placing the recipient containing the DBSA solution and MNP in an ultrasonic bath (Testlab, model TB04), operating with a power of 160 W and a frequency of 40 kHz. After that, a brown emulsion was obtained. Then, ethylenedioxithiophene (EDOT) monomer (in molar ratios with respect to $CoFe_2O_4$, r_{EDOT}, of 2, 5, and 10) was added, keeping the reaction mixture in the same conditions for 1 h. Finally, ammonium persulfate (APS), in a molar ratio of 1:1 with respect to EDOT, was added, and the reaction mixture was kept 3 h always under ultrasound treatment and mechanical stirring. The product was demulsified with an equal volume of isopropyl alcohol. The blue precipitate obtained was separated by centrifugation at 15000*g* for 10 min at 17 °C, washed with ethanol and Milli-Q water to remove the excess of reactants and oligomers, and dried at room temperature for 24 h.

As it was mentioned above, the synthesis was performed for different values of the molar ratio in the feed:

$$r_{EDOT} = \frac{n_{EDOT}}{n_{CF}} \quad (1)$$

where n_{EDOT} and n_{CF} are the mole numbers of EDOT monomer and $CoFe_2O_4$, respectively.

For comparison, the PEDOT−DBSA polymer was synthesized under the same conditions as $CoFe_2O_4$−PEDOT composites described above, but MNP were not incorporated in the reaction media.

X-ray Diffraction (XRD) Measurements. X-ray powder diffraction analysis of nanoparticles and composites was performed with a Philips X-Pert diffractometer using Cu Kα radiation (λ = 0.154056 nm); the average crystallite size was determined via the Scherrer equation

$$d_C = \frac{A\lambda}{\beta \cos(\theta)} \quad (2)$$

where A is a shape factor, taken here as 0.9, β is the full width at half-maximum of the peak, and θ is the corresponding Bragg angle.

Electron Microscopy Studies. The particle size and morphology of particles and composites were studied by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). SEM analysis was performed using a Zeiss Supra 40 Gemini microscope equipped with an

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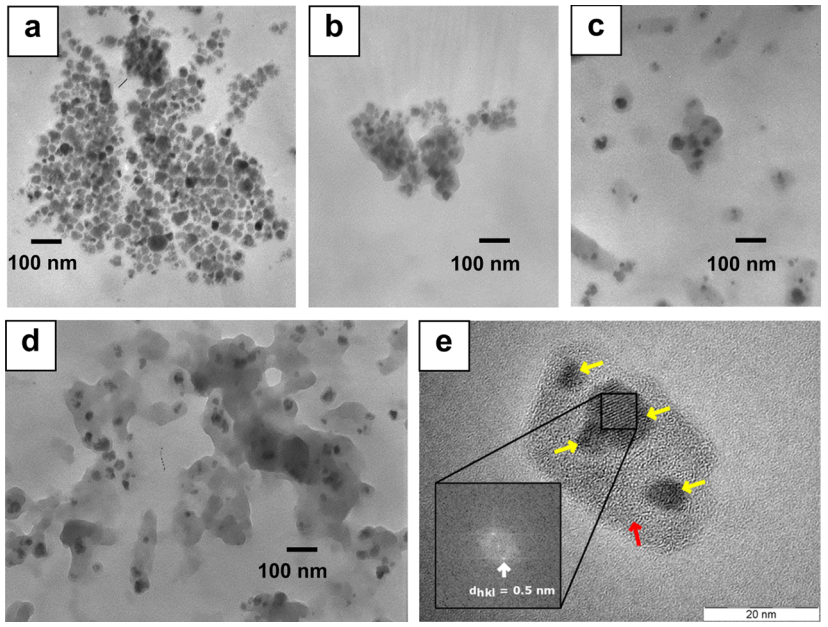

Figure 1. TEM and HR-TEM images of $CoFe_2O4$ nanoparticles and $CoFe_2O_4$−PEDOT composites: (a) TEM image of $CoFe_2O_4$ nanoparticles after polymerization treatment (without monomer); (b) TEM image of composite with $r_{EDOT} = 2$ (c) TEM image of composite with $r_{EDOT} = 5$; (d) TEM image of composite with $r_{EDOT} = 10$; (e) HR-TEM image of composite with $r_{EDOT} = 5$, yellow arrows: MNP; red arrow: PEDOT. Inset: FFT analysis of a 40 nm^2 area of a $CoFe_2O_4$ nanoparticle region.

EDS detector. The samples were prepared by placing a small amount of each solid (nanoparticles or composites) on one side of a carbon tape. EDS measurements were performed in the same experiment. TEM observation was performed by using a transmission electron microscope (Philips EM 301). High-resolution transmission electron microscopy (HR-TEM) bright-field imaging was performed by using a transmission electron microscope (Philips CM200 UT) with a LaB6 thermoelectric emission filament and ultra-Twin lens with a resolution of 0.19 nm. Each material (nanoparticles or composites) was suspended in acetone, and ∼10 μL of each suspension was dripped on a TEM grid and dried prior to insertion into the TEM column.

Thermal Analysis. Thermogravimetric analysis (TGA) of $CoFe_2O_4$ nanoparticles, CoFe2O4-PEDOT composites, and PEDOT polymer was performed by using a simultaneous thermobalance TG-DTA 50 (Shimadzu). The TGA thermograms were recorded for 10−20 mg of each sample at a heating rate of 10 °C/min in the temperature range of 25−800 °C under an air atmosphere.

Fourier Transform Infrared Spectroscopy (FTIR) Characterization. The infrared (IR) measurements of composites, nanoparticles, and polymer were performed by using a FTIR Nicolet 8700 spectrometer in the range 400−4000 cm^{-1}, with a resolution of 4 cm^{-1}. The samples were pressed into pellets prepared by dispersing 0.5 mg of each one in 150 mg of KBr. For each sample, 32 scans were accumulated.

Electrical Conductivity Measurements. The DC conductivity of the different samples was measured on pressed circular pellets (1 cm diameter) by using a Teq-03 (Nanoteq, Buenos Aires, Argentina) potentiostat under computer control. Following Ohm's law, a known current was applied, and the potential difference was measured and averaged during 120 s. The pellet thickness was measured with a caliper to compute the conductivity.

Magnetization and Magnetoresistance Studies. A Lakeshore 7400 vibrating sample magnetometer (VSM) was used for recording magnetization curves at room temperature. The samples were prepared by packing with Teflon tape 10−20 mg of each composite. Also, two different primary remanent magnetization curves were measured at room temperature: isothermal remanent magnetization (IRM) and DC demagnetization (DCD) curves. For the IRM experiments, initially the sample was totally demagnetized at room temperature. Then, a small external field H was applied and subsequently removed, and the remanence was measured, M_{IRM}. The process was repeated increasing the external magnetic field up to 1 T. At this field, the remanence reaches its saturation value, $M_{IRM}(\infty)$. For the DCD curves, first the sample was saturated. Then, a small external field H, in the direction opposite to the magnetization, was applied. Finally, the external field was switched off, and the remanence was measured, M_{DCD}. This procedure was repeated, increasing the field H, until the saturation in the opposite direction is reached.

The resistance of the different samples was also measured in the presence of an applied magnetic field. Contacts using copper wires (100 μm of diameter), attached with silver paste to the pellets and disposed in a planar configuration, were used to perform standard two- and four-terminals techniques, with similar results in both cases. In this way, the contact resistance and the thermoelectric voltages of each terminal can be ruled out, disregarding their contribution to the measurement of the bulk resistance. To avoid overheating, measurements were performed with a Keithley 2614B source meter by applying 10 ms square voltage pulses at 1 Hz rate and by measuring the current during the 50% last part of the pulse. Details of this technique can be found elsewhere.[49] Magnetic field was varied between −0.7 and 0.7 T and incremented at a rate of 5.0 mT s^{-1}. To minimize slow drifts possibly caused by polymer degradation, as suggested by Lupton et al.,[50] the external magnetic field was applied after the electric signal was

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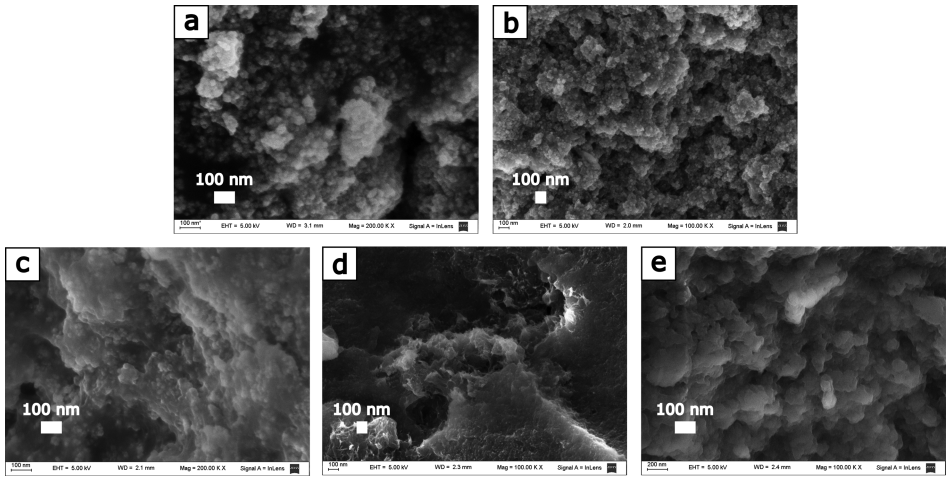

Figure 2. SEM images of $CoFe_2O_4$–PEDOT composites: (a) $CoFe_2O_4$ nanoparticles after polymerization treatment (without monomer); (b) r_{EDOT} = 2; (c) r_{EDOT} = 5; (d) r_{EDOT} = 10; (e) PEDOT.

stabilized. Also, multiple magnetoresistance measurements were performed and averaged.

The percent magnetoresistance (MR%) was calculated following

$$MR\% = \frac{R_H - R_0}{R_0} \times 100 \quad (3)$$

where R_H is the resistance at the applied magnetic field, H, and R_0 is the resistance in the absence of a magnetic field.

RESULTS AND DISCUSSION

Particle Size and Composites Morphology. The morphology of the cobalt ferrite particles obtained here corresponds to a spherical-like shape aggregated in clusters, very similar to those of Antonel et al.[3] and Muñoz Resta et al.,[45] as they were prepared with the very same technique. In Figures 1a–d TEM images of $CoFe_2O_4$–PEDOT composites are shown. The TEM image of pure $CoFe_2O_4$ nanoparticles, after the same treatment employed for the polymerization of EDOT, is observed in Figure 1a. The particle size, as verified by TEM imaging with the aid of the ImageJ software, was found to be d_P = 14 ± 3 nm, very similar to the size of $CoFe_2O_4$ nanoparticles without treatment. This result indicates that DBSA effectively protects $CoFe_2O_4$ nanoparticles from the reaction medium. Besides, the particle size is within the range of monodomain magnetic particles, which for cobalt ferrite falls between a minimum of 7–9 nm[22,51] and a maximum of about 60–70 nm.[52,53]

Also, in Figure 1 it is clear that high r_{EDOT} favors the dispersion of the nanoparticles as they appear more separated with the increase in r_{EDOT}. It is worth mentioning that these MNP act as catalyst for EDOT polymerization, since the polymerization yield increases significantly when they are present in the reaction medium. From Figures 1b to 1d there is a marked change in the composite morphology. For r_{EDOT} = 2 (Figure 1b) the polymer appears mostly covering the MNP, whereas for r_{EDOT} = 10 the MNP appear dispersed in a large polymer matrix, the material with r_{EDOT} = 5 showing an intermediate morphology. This is interpreted considering that, first, PEDOT is produced preferably around $CoFe_2O_4$ nanoparticles, and for higher r_{EDOT} the conducting polymer grows further giving rise to a homogeneous polymeric matrix with the nanoparticles aggregated in clusters; these in turn dispersed in an approximately uniform way. These features were also observed previously for $CoFe_2O_4$–PANI[3] and $CoFe_2O_4$–PPy[45] composites. Figure 1e shows a typical HR-TEM image of a composite with r_{EDOT} = 5. The nanoparticles (dark gray, indicated by yellow arrows) are surrounded by the polymer matrix (gray region, indicated by the red arrow). The high resolution of this image evidences the crystallinity of the nanoparticles in contrast with the amorphous nature of the polymer. Fast Fourier transform (FFT) analysis of the nanoparticle (Figure 1e, inset) shows a d_{hkl} of 0.5 nm, corresponding to the (111) spinel family of lattice planes. The morphology of some of the obtained materials, as observed by SEM, is shown in Figures 2a–e; Figure 2e shows an image of PEDOT without MNP for comparison.

Similarly to TEM observation, different morphologies are found for low and high values of r_{EDOT}. The composite with very low polymer content (r_{EDOT} = 2, Figure 2b) shows a morphology that is very similar to that of bare $CoFe_2O_4$ nanoparticles (Figure 2a). When increasing the PEDOT content (r_{EDOT} = 5, Figure 2c), composites have a relatively smooth topography, as a consequence of being dominated by the polymer presence. Finally, for high polymer content (r_{EDOT} = 10) the materials show a more regular surface, very similar to the pure polymer (Figure 2e). The chemical composition of the MNP was verified from SEM-EDS measurements (not shown), resulting in a Fe:Co molar ratio of 2:1, thus confirming that the product obtained was effectively $CoFe_2O_4$.

As was shown in Figure 1, the MNP appear aggregated in clusters in the composites with PEDOT. To have an estimation of the particle–particle separation inside each cluster, the distances between MNP were measured with the aid of the ImageJ software, and the resulting histograms are presented in Figures 3a–c, with the corresponding log-normal distributions. For each composite, ∼100 particle–particle separations inside each cluster were measured. In the case of the composite with r_{EDOT} = 10, TEM images show that the distance between clusters is significantly larger than the particle–particle separation inside each cluster while is not the case for $r_{EDOT} \leq 5$. Therefore, in this case, about 75 distances between clusters were measured, and the resulting histograms are shown in Figure 3d, also with the corresponding log-normal distribution.

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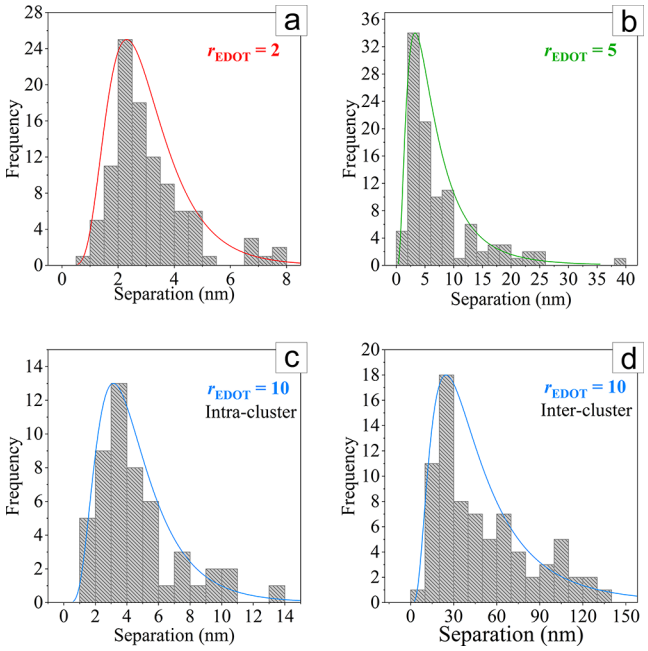

Figure 3. Particle−particle separation for $CoFe_2O_4$−PEDOT composites with (a) r_{EDOT} = 2, (b) r_{EDOT} = 5, (c) r_{EDOT} = 10 (intracluster), and (d) r_{EDOT} = 10 (intercluster).

From the log-normal distributions for the particle−particle separation inside clusters in the composites with different r_{EDOT}, first the mean values and the standard deviations were calculated. The obtained values are 3 nm (standard deviation = 2 nm) for the composite with r_{EDOT} = 2, 7 nm (standard deviation = 4 nm) for the composite with r_{EDOT} = 5, and 5 nm (standard deviation = 3 nm) for the composite with r_{EDOT} = 10. Also, the modes were calculated, obtaining a value of 3 nm for the composite with r_{EDOT} = 2, 6 nm for the composite with r_{EDOT} = 5, and 4 nm for the composite with r_{EDOT} = 10. These results suggest that within experimental error the distance between MNP inside clusters remains approximately constant and is independent of r_{EDOT}. On the other hand, the cluster−cluster separation increases noticeably in the composite with r_{EDOT} = 10, having a mean value of 50 nm (standard deviation = 30 nm) and a mode value of 40 nm. These results indicate that in the composites the MNP are aggregated in clusters, with an interparticle separation distance essentially constant (∼3−6 nm) but where two regimes can be distinguished for the intercluster separation: for high MNP concentration (r_{EDOT} = 2) a particle dominated composite is obtained, with an intercluster separation similar to the interparticle distance, while for a low MNP content (r_{EDOT} = 10), a polymer-dominated material is obtained, where the distance between clusters is clearly larger than the interparticle distance. That means that for low r_{EDOT} ($r_{EDOT} \leq 5$) the polymer appears mostly covering the MNP giving as a result an interparticle separation approximately constant. In other words, the distances between MNP are all very similar in composites with $r_{EDOT} \leq 5$ and are determined by the PEDOT layer that grows covering the MNP. On the other hand, for r_{EDOT} = 10 there is a higher monomer concentration in the synthesis medium, resulting in faster growth of PEDOT. Initially, the polymer appears covering the ferrite particles, resulting in clusters as before, and after that the excess monomer present polymerizes around the clusters, resulting in larger separation between them.

Crystalline Structure. The XRD patterns of the nanoparticles obtained are shown in Figure 4, where a typical

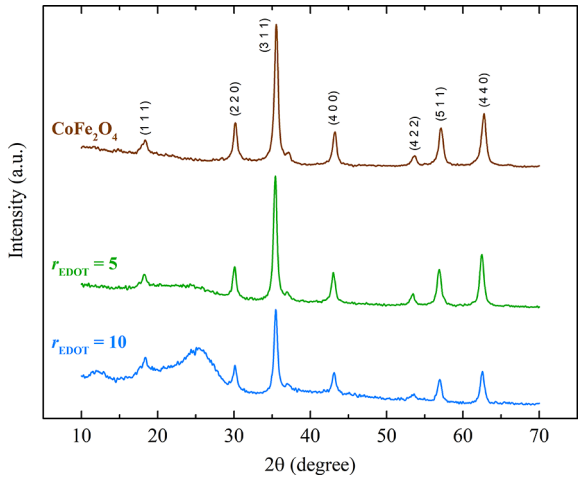

Figure 4. XRD diagram/patterns of $CoFe_2O_4$ nanoparticles and composites for different r_{EDOT} ratios. Nanoparticles synthesized at 80 °C reveal an inverse spinel structure.

inverse spinel pattern is observed (ICDD 03-0864, JCPDS 22-1086) with the space group *Fd3m*, very similar to that of Fe_3O_4.[22,54] The ferrite lattice parameter was determined by using the (311) peak and was found to be $a = b = c$ = 8.369 Å, which is close to the values reported for $CoFe_2O_4$ nanoparticles.[55−57] Besides, the obtained value of 8.369 Å is smaller than 8.395 Å, which corresponds to the lattice parameter of bulk $CoFe_2O_4$.[22] This indicates that in $CoFe_2O_4$ nanoparticles there are more defect sites in comparison with bulk $CoFe_2O_4$—a fact that could be explained taking into account the high area/volume ratio in nanostructured systems. The diameter of the crystallites, d_c, prepared here was estimated through eq 2 by using the (311) peak, resulting in d_c = 15.4 nm, which is in agreement with the TEM measurements and with the previously reported results.[22,47]

Figure 4 also shows the XRD patterns for composites with r_{EDOT} = 5 and r_{EDOT} = 10. For smaller r_{EDOT}, the diffractograms do not show the presence of the amorphous phase associated with the polymer and are essentially identical to the one shown for pure $CoFe_2O_4$ nanoparticles. It is clearly observed that for a polymer dominated material (r_{EDOT} = 10) a broad diffraction band around 2θ = 25°, characteristic of the low crystallinity of the polymer, is observed. Also, these results are consistent with TEM and SEM observations, which show particle-dominated composites for r_{EDOT} = 2 and polymer-dominated materials for r_{EDOT} = 10. Note that for r_{EDOT} = 5 the polymer band is present but very weak, consistent with a transition between NMP and polymer-dominated materials. Comparing these results with those obtained for composites of $CoFe_2O_4$ nanoparticles and PANI[3] or PPy,[45] with PANI or PPy a higher amount of polymer is incorporated in the materials, giving as a result polymer-dominated composites even with small values for the respective monomer:ferrite molar ratios, r_{ANI} or r_{Py} (5 in the case of PANI[3] and 3.5 in the case of PPy[45]). This result is consistent with the lower polymerization rate for EDOT compared with pyrrole and aniline.

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Thermal Decomposition and Composite Composition. To study the thermal decomposition of the resulting composites and to gain insight into their composition, thermogravimetric analysis (TGA) in air was conducted (Figure 5); it is observed that PEDOT-DBSA is completely

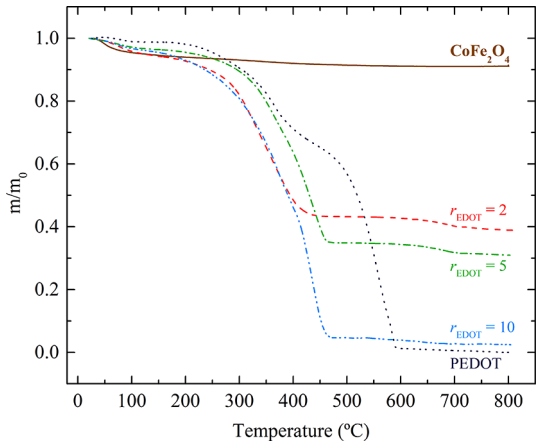

Figure 5. TGA measurements of cobalt ferrite, PEDOT, and composites, plotted as relative mass (m/m_0) as a function of temperature.

decomposed by oxidation and the ferrite particles undergo only a small mass loss, whereas the composites give intermediate results, thus confirming the composite formation. The features in Figure 5 can be explained as follows: first, when increasing the temperature T, an initial mass loss is observed, attributable to removal of water from the material; this loss ends at about 250 °C, where the curves are almost leveled. At higher temperatures, a pronounced decrease is observed, corresponding to polymer decomposition, starting at ∼307 ± 5 °C (as estimated from the curve derivative, not shown), with a second step at about 500 °C, and ending at ∼600 °C for PEDOT-DBSA. This is in agreement with literature reports, where PEDOT decomposition occurs mainly in the range ∼300−450 °C,[58] but mass loss is observed up to ∼600 °C.

On the other hand, for $CoFe_2O_4$−PEDOT composites the polymer decomposition starts at 260 ± 10 °C (independent of composition within experimental error) and takes place up to ∼450−480 °C, without a discernible second stage. The differences comparing with the PEDOT-DBSA case can be attributed to a catalytic effect of the ferrite particles on the polymer decomposition.

Pure ferrite particles show, after some water elimination, a small decrease probably due to loss of surface hydroxyl groups. From the TGA results, the composite's composition can be estimated, assuming that the mass loss at T < 250 °C is due to water elimination, that the remaining mass at T = 800 °C corresponds to the ferrite particles with no polymer remaining, and introducing a correction for the mass change of the cobalt ferrite particles between 25 and 800 °C. The results for the $CoFe_2O_4$ mass fraction in the composite, f_{CF}, and the measured polymer/ferrite molar ratio, r_m, are presented in Table 1.

Electrical Conductivity. The electrical conductivity of the composites depends of the monomer−ferrite ratio, being in the range 10^{-5}−10^{-3} S cm^{-1} with a monotonous decrease as the ferrite contents increases, as can be observed in Table 2. On the other hand, PEDOT prepared in the same conditions as

Table 1. Composite's Composition as Found by Thermogravimetric Analysis

feed composition, r_{EDOT}	measured composition, r_m	cobalt ferrite mass fraction, f_{CF}
2.0	2.1 ± 0.1	0.45 ± 0.02
5.0	3.2 ± 0.3	0.34 ± 0.03
10.0	57 ± 9	0.13 ± 0.02

Table 2. Room Pressure and Temperature Conductivities of PEDOT and Composites with Different r_{EDOT} Ratios

sample	conductivity (S cm^{-1})
composite feed composition, r_{EDOT}	
2.0	(2.2 ± 0.8) × 10^{-5}
5.0	(4.5 ± 1.5) × 10^{-4}
10.0	(6.0 ± 3.0) × 10^{-3}
PEDOT (w/o MNP)	0.3 ± 0.1

the nanocomposites gives a conductivity of 0.3 S cm^{-1}. This value is similar to several results reported for PEDOT obtained by using APS or Fe(III) as oxidizing agents. For example, Choi et al.[58] found bulk conductivities for PEDOT also synthesized with APS as oxidant and DBSA of 1−10 S cm^{-1}; Morvant et al.[59] prepared thick films of PEDOT, obtaining in situ conductivities in the range 0.2−13.0 S cm^{-1}, depending on growth conditions; Corradi et al.[60] synthesized PEDOT at different reaction temperatures, using Fe(III) as oxidizing agent, and in this case the maximum electrical conductivity achieved was ∼5 S cm^{-1}.

The electrical conductivity values for the composites show that the presence of the MNP highly affects the polymer electrical conductivity, since even those with the highest r_{EDOT} gives composites with low conductivities. Nevertheless, the minimum electrical conductivity value achieved (∼10^{-5} S cm^{-1}) suggests that down to the lower r_{EDOT} explored PEDOT retains an electrical conductivity path, indicating that the polymer can percolate through the material.

Additionally, it should be mentioned that the conductivity of the composites is far away from the values expected from the general effective media (GEM) theory, which quantitatively describes the conductivity of a binary mixture as a function of the conductivities and the volume fraction of each component.[61,62] The observed behavior indicates the strong effect that the MNP have on the conductivity of PEDOT as even a small fraction (r_{EDOT} = 10) decreases the conductivity of the composite far below from the expected values determined by the GEM model (≈1/50). The same effect, with similar values, was observed for PANI and Fe_3O_4 or $CoFe_2O_4$ composites.[1,3] This indicates that the inclusion of MNP has a long-range effect which is probably related to the generation of mechanical stress and to a change in the electrical mobility of carriers, by both introducing additional scattering centers and by producing different arrangement of the polymer chains, compared with the pure PEDOT. This last fact is due to the initial growth of the polymer around the MNP, as suggested by SEM images, resulting in less crystallinity and thus a lower electrical conductivity.

IR Spectroscopy. Figure 6 shows the IR spectra of PEDOT, $CoFe_2O_4$ nanoparticles, and PEDOT−$CoFe_2O_4$ composites with different r_{EDOT} ratios. The IR response of PEDOT (Figure 6, top) has been reported by several authors.[48,58,63,64] The most relevant bands of the spectra shown in Figure 6 will be discussed in the following. The

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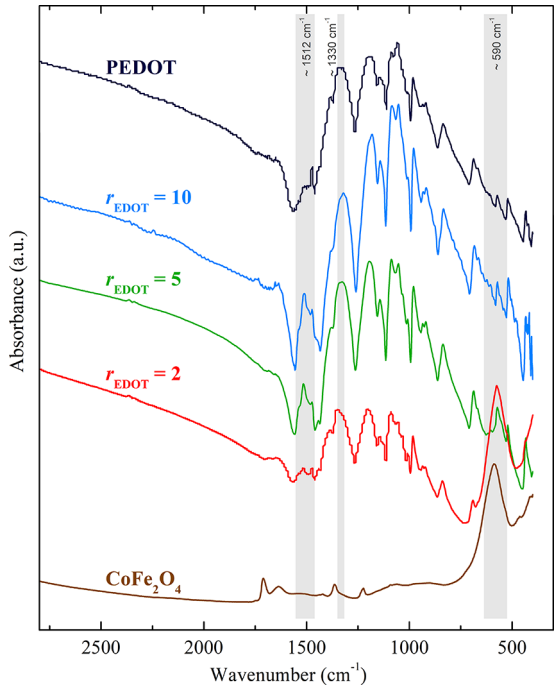

Figure 6. IR spectra of PEDOT, $CoFe_2O_4$ nanoparticles, and PEDOT−$CoFe_2O_4$ composites with different r_{EDOT} ratios.

vibrational band at around 1512 cm^{-1} corresponds to C═C or C−C ring stretching of the thiophene ring, and the one around 1330 cm^{-1} corresponds to C═C or C−C ring stretching of the quinoid structure of the thiophene ring. Vibrational bands at 1190, 1142, and 1055 cm^{-1} are due to C−O−C bond stretching in the ethylenedioxy group. The band around 920 cm^{-1} is originated from the ethylenedioxy ring deformation. Vibration modes of the C−S bond in the thiophene ring are also seen at 980, 835, and 685 cm^{-1}. In the spectrum of cobalt ferrite (bottom), on the other hand, besides surface OH vibrations ca. 3500 cm^{-1} (not shown) and other minor bands, the main lattice band at 590 cm^{-1} is clearly visible. In the composite spectra, this band shows decreasing intensity as r_{EDOT} increases, as expected. The absence of additional peaks in the range between 1600 and 1800 cm^{-1}, which would indicate carbonyl groups formation by oxidation, demonstrates that the overoxidation of the polymer can be excluded. There are some differences between the polymer bands in pure PEDOT spectrum and those in the composites, which indicates that some interaction of ferrite nanoparticles with polymer chains takes place. The most prominent change is observed in the vibrational band at 1512 cm^{-1}, which corresponds to C═C or C−C ring stretching of the thiophene ring: first, a displacement to 1520 cm^{-1} is observed for the composite with r_{EDOT} = 2; also, this band undergoes a splitting, giving a second one at 1470 cm^{-1}, with the A_{1470}/A_{1510} ratio (absorbance ratio) increasing with ferrite content.

Magnetization Behavior and Magnetic Interactions. Figure 7 shows the mass magnetization, M, as a function of the applied magnetic field H for the bare particles and composites, all measured at room temperature. The curve for the bare particles is similar to others reported in the literature,[22,45,47,51] showing hysteresis, which reveals ferromagnetic behavior. $CoFe_2O_4$ MNP synthesized and used in this work can be considered as magnetic monodomain particles, since their average size was found to be d_P = 14 ± 3 nm, as it was

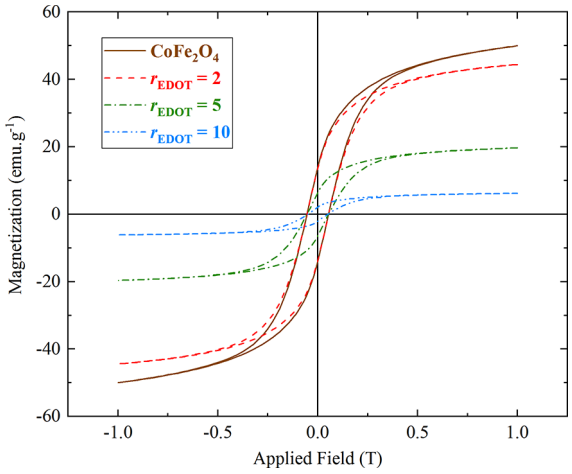

Figure 7. Magnetization curves of $CoFe_2O_4$ particles and composites with different r_{EDOT} measured at room temperature.

observed in TEM images. This average size lies between the critical single domain size (70 nm)[52,53] and the superparamagnetic threshold (7−9 nm)[22,51] in the case of $CoFe_2O_4$ MNP. That means that $CoFe_2O_4$ MNP having an average size between 7−9 and 70 nm are expected to be in the monodomain regime, showing a ferromagnetic behavior at room temperature, as it was observed in the magnetization hysteresis loops shown in Figure 7. The fact that $CoFe_2O_4$ MNP show ferromagnetism at room temperature is due to their high magnetocrystalline anisotropy.[22,65,66] Following Muñoz Resta et al.,[45] for small and single domain ferromagnetic particles, the coercivity is limited by the net anisotropy of these particles, which includes the magnetocrystalline anisotropy. Moreover, the coercivity is proportional to the anisotropy constant,[66] giving as a result that $CoFe_2O_4$ MNP show ferromagnetic behavior at room temperature, a result also found by other authors.[3,22,45,47,55,65,67]

The magnetization is referred to the total composite mass, thus the curves have smaller M values as the contents of magnetic particles decreases. In particular, the maximum magnetization reached at H = 1 T, M_{max} (which has not yet reached its saturation value M_s), decreases as the polymer content increases because PEDOT is essentially a nonmagnetic material. M_s can be estimated by fitting the M vs H curve with a simplify law of approach to the saturation:[68]

$$M = M_s\left(1 - \frac{a}{H} - \frac{b}{H^2}\right) \quad (4)$$

where a and b are appropriate constants.

The obtained M_s value for the bare $CoFe_2O_4$ MNP (59 emu g^{-1}) is in accordance with the values published for MNP of similar diameters.[22,45,69]

Interestingly, although the mass fraction of the MNP for the r_{EDOT} = 2 composite is close to 45% of the composite mass, its M_{max} value is almost 85% of the M_{max} value for the bare particles. Also, for the r_{EDOT} = 5 and r_{EDOT} = 10 composites their M_{max} is higher than the one expected for their mass fraction of MNP. The same conclusions are found if we consider the estimated M_s values. This result is clearly indicating that the magnetization of the composites is not obeying a simple mass dilution of the MNP content. Instead, an additional ferromagnetic (FM) interaction should be playing an important role. As the MNP are embedded in

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PEDOT, which is an electrical conducting material, it is possible to have a Ruderman−Kittel−Kasuya−Yosida (RKKY) mechanism which produces an indirect exchange coupling between the magnetic moment of the MNP through the electrical carriers (holes) of PEDOT.[70]

The RKKY coupling will be intensely ferromagnetic for MNP that are closer than a distance d_{FM} while for longer distances (d), it will oscillate periodically from antiferromagnetic to ferromagnetic and decays as d^3. d_{FM} can be roughly estimated as

$$d_{FM} = \frac{4.49}{2k_F} = \frac{4.49}{2(3\pi^2 n)^{1/3}} \quad (5)$$

where k_F is the Fermi wave vector and n the density of free carriers. An estimation of the n value for our composites can be done as follows: As the electrical conductivity is $\sigma = n\mu q$ (where n is the density of carriers, μ their mobility, and q the elementary charge), and by considering the span of μ values reported for PEDOT materials[71−73] synthesized with close counterions, but discarding those extremely high values, corresponding to samples prepared in a particular way to reach the most higher values of electrical conductivities ($\sigma >$ 6000 S cm^{-1}), we obtain that

$$0.1\ \text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1} \le \mu \le 10\ \text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$$

which, for our measured σ in the case of PEDOT:DBSA (0.3 S cm^{-1}), limits the n values to $2 \times 10^{23}\ \text{m}^{-3} \le n \le 2 \times 10^{25}\ \text{m}^{-3}$. In this way, we obtain from eq 5 that 3 nm $\le d_{FM} \le$ 13 nm. Within this interval of possible d_{FM} values, this result is in accordance with the observed behavior of M_{max} and M_s for the r_{EDOT} = 2 and r_{EDOT} = 5 composites. That is by considering the distance distribution of MNP for each composite (see Figure 3), it can be observed that even for the extreme case of $d_{FM} \approx 3$ nm a large portion of them will be coupled FM, yielding to a cluster-like magnetic behavior and, concomitantly, to an increase of their M_{max} (or equivalently of M_s). The RKKY influence on the M_s of a magnetic material surrounded by an electrical conducting matrix has been already observed, for example, in $CoFe_2O_4$ MNP interconnected by an Au matrix, where M_s presents an oscillatory damped behavior as a function of the Au width between MNP.[74]

To compare more closely the above curves, they are presented in Figure 8 in the form of relative magnetization, M/M_{max}, as a function of the magnetic field. The inset shows the curves in the full range, where it is observed that all the curves merge for high field values. The main graph shows an enlarged view of the low field region, revealing that the remanence ratio, M_r/M_{max}, increases as the polymer contents increases, and also a relatively small decrease (in terms of the H range) in the coercivity H_c is found for the composite with r_{EDOT} = 10. These results suggest that in terms of coercivity the magnetic properties of the composites also show an abrupt change when passing from particle-dominated composites (r_{EDOT} = 2) to a polymer-dominated material (r_{EDOT} = 10), as it was observed in SEM and TEM observations and in XRD studies. These results, summarized in Table 3, also support the framework of a RKKY interaction between MNP and mediated by the electrons of PEDOT, already discussed for the M_{max} behavior, indicating that there is a change in the magnetic properties when the particles are included in the composite. Otherwise, if a simple "dilution" effect was taking place, all the normalized curves should be coincident. Therefore, the remanence ratio

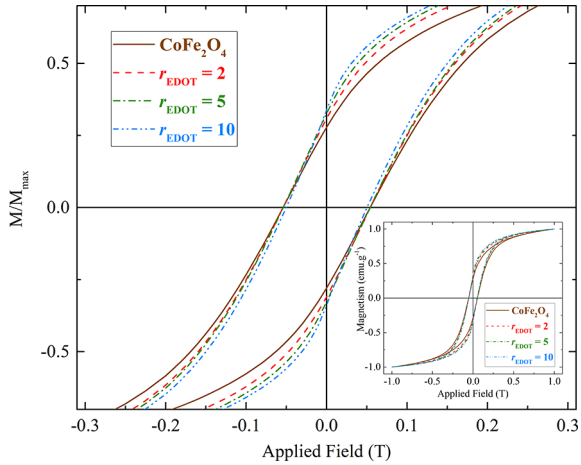

Figure 8. Normalized magnetization curves for $CoFe_2O_4$−PEDOT composites, for different r_{EDOT}. The insets show the full curves, while the main graph present the curves with an enlargement around H = 0.

increases with r_{EDOT}, sustaining the presence of FM interactions between the magnetic NP at the expense of the polymer matrix.

To gain insight into the type and strength of interaction between MNP, isothermal remanence magnetization (IRM) and DC demagnetization (DCD) curves, both at room temperature, were measured. The results, well-known as Henkel plots,[75] are shown in Figure 9. The dashed line corresponds to eq 6 and represents the expected behavior for a noninteracting system, as predicted by the Stoner−Wohlfarth model:[76]

$$\frac{M_{DCD}}{M_R(\infty)} = 1 - \frac{2M_{IRM}}{M_R(\infty)} \quad (6)$$

As can be observed, all the composites show a negative deviation from the dashed line that increases with decreasing r_{EDOT} (or the polymer content), indicating that the main interparticle magnetic interaction is dipolar.[77] This is an interesting result due to the fact that regardless of the existence of a FM coupling between MNP mediated by the RKKY interaction, the dipolar interaction is the dominant one in the magnetization and demagnetization processes.

A possible interpretation of this result can be done considering that the RKKY interaction strongly couples ferromagnetically all the MNP that are at distances less than the estimated interval for d_{FM} (3−13 nm), causing them to act as a single magnetic cluster. In this framework, the IRM and DCD curves would reveal the existence of magnetic dipolar interactions between clusters. In fact, it can be observed that dipolar interactions are weak for the composite with r_{EDOT} = 10 and strong for the composite with r_{EDOT} = 2 and have an intermediate magnitude for the composite with r_{EDOT} = 5. This result is in accordance with the expected spatial dependence of the dipolar interaction on the average distance between magnetic interacting particles, which could then be associated with the mentioned clusters of MNP (see Figure 3).

From the IRM measurements additional information about the reversible contribution to the magnetization, M_{rev}, can be obtained, by considering the following relation:

$$M_{rev}(H) = M'(H) - M_{IRM}(H) \quad (7)$$

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Table 3. Coercive Field and Remanence Ratio of Cobalt Ferrite and Composites

material	$CoFe_2O_4$	r_{EDOT} = 2	r_{EDOT} = 5	r_{EDOT} = 10
$H_c/10^{-4}$ T	543 ± 6	543 ± 4	541 ± 7	504 ± 7
M_r/M_{max}	0.278 ± 0.003	0.308 ± 0.002	0.326 ± 0.003	0.339 ± 0.003
M_r/M_s	0.233 ± 0.001	0.273 ± 0.002	0.289 ± 0.002	0.304 ± 0.001

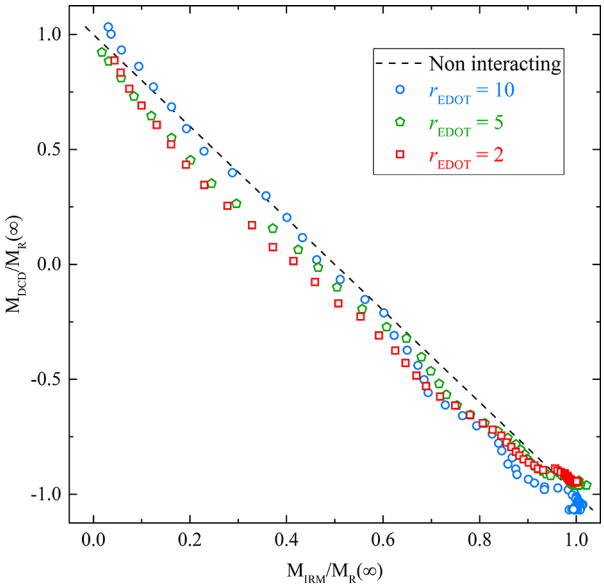

Figure 9. Henkel plot for $CoFe_2O_4$–PEDOT composites with different r_{EDOT} ratios.

where M' is the magnetization of the first magnetization curve and M_{IRM}, as the remanent contribution, corresponds to the irreversible part of the magnetization. Results for the normalized M_{rev} are shown in Figure 10. It can be seen that

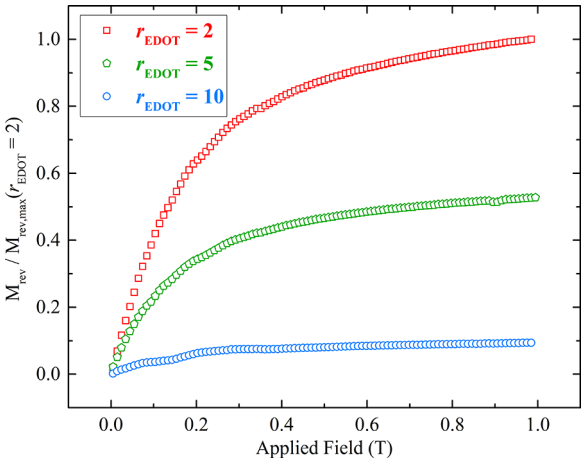

Figure 10. Normalized reversible magnetization for $CoFe_2O_4$–PEDOT composites with different r_{EDOT} ratios.

M_{rev} increases with the applied magnetic field for all the composites, being this increment more pronounced up to ~0.4 T. Also the increment in M_{rev} with H depends on r_{EDOT}, showing a higher value as the mass fraction of the MNP increases.

Magnetoresistance. Figure 11 shows MR%, computed from eq 3, of $CoFe_2O_4$–PEDOT composites at room temperature. MR% depends on r_{EDOT}, being positive and

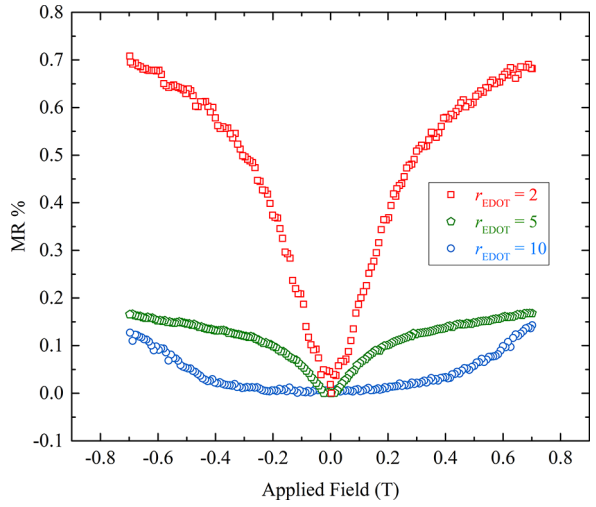

Figure 11. Magnetoresistance for $CoFe_2O_4$–PEDOT composites with different r_{EDOT} ratios.

reversible and increasing in value with the applied magnetic field, as already seen by Gu et al. for composites of PANI–magnetite,[42] by Muñoz Resta et al. for composites of PPy–$CoFe_2O_4$[45] and Klemm et al.[50] for PEDOT:PSS polymer. Furthermore, the magnetoresistance decreases with increasing r_{EDOT} and becomes negligible for pure PEDOT, indicating its correlation with the presence of MNP. MR% reached values up to 0.7% for composites with r_{EDOT} = 2 while for composites with $r_{EDOT} \geq 2$ the maximum MR% is about 0.15%. Moreover, for the composite with r_{EDOT} = 2 there is a linear relationship between MR% and H, in the low field region (up to ~0.3 T), which favors considering this material as a promising candidate to be applied as a magnetic sensor. To the best of our knowledge, this is the first time that magnetoresistance measurements of PEDOT–$CoFe_2O_4$ composites are investigated. The reversible behavior of MR% with the magnetic field and its dependence with the MNP content leads us to consider that its microscopic origin may be related to what generates the reversible part of the magnetization. Indeed, it should be noted that the shape of MR% vs H and M_{rev} vs H (Figures 11 and 10, respectively) is quite similar (at least for the composites with r_{EDOT} = 2 and r_{EDOT} = 5), effectively suggesting that the origin of the observed phenomena is the same in both cases. To better visualize the correlation between the magnetoresistance and the reversible magnetization, the relative magnetoresistance, MR/MR_{max}, vs the relative reversible magnetization, $M_{rev}/M_{rev,max}$, is presented in Figure 12.

Figure 12 shows that for MNP dominated materials (r_{EDOT} = 2) a strong dependence of the normalized MR with normalized M_{rev} is found, whereas for the polymer dominated case (r_{EDOT} = 10) there is practically no effect; r_{EDOT} = 5, as before, shows an intermediate behavior. In this way, Figure 12 reveals that the M_{rev} dependence of MR% can be scaled for the composites above a minimum concentration of MNP and confirms that

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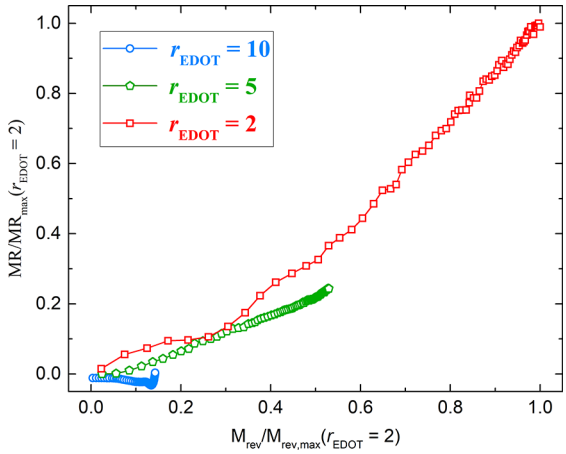

Figure 12. Normalized relative magnetoresistance vs relative reversible magnetization for $CoFe_2O_4$–PEDOT composites with different r_{EDOT} molar ratios.

the magnitude of the observed magnetoresistance is a function of the reversible term of the magnetization.

These results give an interesting clue about the microscopic origin of MR for these composites. Indeed, the nonhysteretic behavior of MR ruled out that the magnetoresistance could be related to an interaction between the electrical carriers and the magnetic moments of MNP or their local magnetic field. Discarding its direct magnetic origin, but considering its dependence with M_{rev}, the magnetic-field-induced rotation of the MNP can be considered as its possible source. In this context, rotation of MNP could stretch the polymer chains as well as narrowing their local section, being consistently two contributions that produce a positive magnetoresistance. Further studies are needed to confirm this hypothesis.

CONCLUSIONS

Composites based on MNP of $CoFe_2O_4$ and the conducting polymer PEDOT in different molar ratios were synthesized chemically by using DBSA as acid media and nanoparticles protecting agent. In these materials the nanoparticles are aggregated in clusters, and the morphology depends on r_{EDOT}. It was also found that the electrical conductivity of the composites decreases as r_{EDOT} increases, being in the range 10^{-5}–10^{-3} S cm^{-1}. These values indicate that the inclusion of MNP has a long-range effect in the electrical conductivity of PEDOT, which is probably related to the generation of mechanical stress and to a change in the electrical mobility of carriers. From the magnetization experiments it can be concluded that in PEDOT–$CoFe_2O_4$ composites exist a RKKY interaction that strongly couples ferromagnetically all the MNP that are at distances less than the estimated interval for d_{FM} (3–13 nm), causing them to act as a single magnetic cluster, giving as a result an increase in the magnetization of saturation and in the remanence ratio with r_{EDOT}. On the other hand, between magnetic clusters exist dipolar interactions, the magnitude of which decreases with the increase in r_{EDOT}. The composites also exhibit positive and reversible magnetoresistance, the magnitude of which increases with the applied magnetic field and decreases with increasing r_{EDOT}, being negligible for pure PEDOT. The applied magnetic field induces the rotation of the MNP, a phenomenon that could stretch the polymer chains as well narrowing their local section, giving as a result an increase in the magnetoresistance with the applied magnetic field. Moreover, for the composite with r_{EDOT} = 2 the maximum MR% is 0.7%, and there is also a linear relationship between the MR% and H in the low field region. This last result favors considering this material as a promising candidate to be applied as a magnetic sensor. All the results obtained and the analysis performed in this work allows to have a physical understanding of the magnetic interactions and their relationship with r_{EDOT}—facts that are very important for the future application of these composite materials.

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Author Contributions

The manuscript was written through contributions of all authors. M.L.M.E. performed the experimental part; C.A. devised and supervised IRM, DCD, magnetoresistance, and conductivity measurements; M.L.M.E., C.A., and P.S.A. analyzed the results; F.V.M. contributed with the discussions; P.S.A. devised and supervised all the experiments and wrote the manuscript. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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