Characterization and selective deposition of carbon nanotubes from carbon nanoparticles mixture using mild acid treatment and electrokinetic manipulation

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Abstract
Particle manipulation is often required in the fabrication of microelectronic devices such as transistors and sensors. In this work, we succeeded in depositing aligned carbon nanotubes (CNTs) from an oxidized conglomerates carbon mixture using a simple low power procedure consisting of mild acid treatment and frequency-dependent dielectrophoretic (DEP) force. The treatment improved the dispersity and solubility of CNTs due to the functional groups introduced on their surface. The DEP force was generated with an AC signal of 1 MHz and 7.07 Vrms to attract the CNTs to a transparent electrode gap of 50 μm. Treatment quality was confirmed and characterized by Raman spectroscopy, Fourier-transform infrared spectroscopy (FTIR), energy dispersive x-ray analysis (EDX) and high-resolution transmission electron microscopy (HRTEM). Ultraviolet-visible spectroscopy (UV-vis) and dynamic light scattering (DLS) were used to analyze the dispersity and solubility of carbon particles and their size distribution in different solvents. The morphology of the deposited CNTs and amorphous carbon were observed by optical microscope and field-emission scanning electron microscope (FESEM). The procedure used in this work is cost-effective, scalable and essential for future assembly. Furthermore, the transparency of the system makes it suitable for real-time observation, transparent sensors, and the ability to integrate it into microfluidic channels.

1. Introduction

Carbon nanotubes (CNTs) are one-dimensional cylindrical nanostructures composed of graphene nanosheets. The remarkable thermal, electrical, optical, and mechanical properties of CNTs enabled a large variety of applications in electronics, medicine, and construction [1–3]. The CNT diameter depends on the number of walls, ranging from few nanometers up to several hundred nanometers, while their length depends on the synthesis time and ranges typically from several hundred nanometers to several tenths of micrometers or even longer. However, the synthesis of CNTs in non-optimal conditions such as at low temperatures or low gas concentration may lead to the formation of other carbon forms along with the CNTs [4]. The other carbon forms, such as graphene, carbon black, and amorphous carbon, may be present at the same growth condition at low percentages. Optimized synthesis methods still produce heterogeneous mixtures of carbon species that vary in their chirality, length, and diameter [5].

The presence of amorphous carbon with CNTs limits their commercial applications. Additionally, different CNT species within the same batch might lead to a device with unpredicted behavior. CNT separation and
selective deposition are essential, as they impact the device’s structural and electrical behavior. For example, the integration of long single-walled carbon nanotube (SWCNT) in carbon nanotube field-effect transistors (CNTFET) yields a more homogeneous transistor characteristic compared to a device with short SWCNT [6].

A simple and scalable process is required to selectively deposit specific particles from a mixture of different structure particles. The current processes involve two primary stages before the final deposition or separation of the target structure. The first stage is sample treatment and functionalization, and the second stage is dispersing the sample in a proper medium for further use [7].

The functionalization stage chemically modifies the sample by introducing oxygen-containing groups to the particle surface, such as carboxyl and hydroxyl [8]. The functionalization is achieved either by oxygen plasma treatment [9], gas-phase treatment [10], photo-oxidation [11], or wet chemical methods [12]. The latter method is widely available, requires a simple installation, and it is cost-effective. It utilizes wet chemicals, such as HCL [13], HNO₃ [14], H₂O₂ [15], H₂SO₄ [16], and a mixture of two or more acids [17]. However, harsh acid treatment may cause significant surface defects, and CNTs might lose their outstanding electrical properties. Controlling the temperature and concentration of the acid is crucial in the functionalization process [18]. The dispersibility and bundling between CNTs tubules in a medium are often improved after the treatments.

The second stage is dispersing the treated sample in a proper solvent to ensure that the particles can move and rotate freely [19]. Organic and aqueous solvents are the two most widely used mediums to disperse CNTs and other carbon species. Organic solvents such as dimethylformamide (DMF) [20], 1,2-dichloroethane (DCE) [21], N-methyl-2-pyrrolidone (NMP) [22], ethanol [23], and isopropanol alcohol (IPA) are widely available [24]. Aqueous solvents such as deionized water (DIW) are usually mixed with a surfactant agent to stabilize CNTs [25]. Surfactants such as sodium dodecylbenzene sulfonate (SDBS) [26], sodium dodecyl sulfate (SDS) [27], phosphate-buffered saline (PBS) [28], Pluronic F108 [29], Triton X-100 [30] and sodium cholate (SC) [31]. Organic and alcohol solvents require a sonication right before the deposition to prevent particle aggregation. The increase in the surfactant concentration causes an increment in the medium conductivity and undesirable electrothermal forces [32].

The principle of the extraction and separation of carbon species from each other is the difference in their size, shape, conductivity, and dielectric constants. Size-exclusion chromatography (SEC) is used to separate carbon species dispersed in a surfactant medium based on their size differences [33]. Density-gradient centrifugation (DGU) is another method in which CNT mixtures can be sorted into individual components based on their buoyant density difference [34]. Electrophoresis (EP) and dielectrophoresis (DEP) are electrokinetic forces that utilize electric fields to manipulate CNTs suspended in a liquid medium [35]. EP is a colloidal processing method used to coat conductive substrates with CNTs or CNT composites, such as coating fluorine-doped tin oxide (FTO) electrode with MWCNT/Pt composite to enhance the performance of dye-sensitized solar cells [36]. Recently, EP is used to deposit CNTs on non-conducting substrates such as silicon and rubber [37]. DEP is used to extract metallic SWCNT from a mixture of semiconducting and metallic tubes based on their electrical properties [38]. Compared with the methods above, EP and DEP can selectively deposit CNTs directly into the device at the required location without the need for a transfer phase.

The DEP theory is simple: each particle subjected to a non-uniform electric field has a dipole moment. The dipole moment highly depends on particle geometry and polarizability, which can be expressed as in equation (1) [39]:

\[ p = \nu \alpha E \]

where \( \nu \) and \( \alpha \) are the geometrical factor and the effective polarizability factor, respectively. For a CNT with a shape approximated to slender prolate ellipsoid, the geometrical and polarizability factors are expressed as in equations (2) and (3), respectively:

\[ \nu = \frac{4\pi r_{\text{cut}}^2 l_{\text{cut}}/2}{3} = \frac{4\pi r_{\text{cut}}^2 l_{\text{cut}}}{6} = \frac{\pi d_{\text{cut}}^2 l_{\text{cut}}}{6} \]

\[ \alpha = 3 \varepsilon_0 \varepsilon_m R e [\bar{K}] \]

The term \( K \) is equivalent to the Clausius–Mossotti factor, which depends on the electric conductivity and permittivity of the CNT and the medium. The parallel (along the tube longer axis) and perpendicular (along the tube radial axis) component of the real K factor \( R e [K]^I I \) are given by equations (4)–(6):

\[ R e [K]^{II} = \frac{1}{3} R e \left[ \frac{\bar{\varepsilon}_{\text{cut}} - \bar{\varepsilon}_m}{\bar{\varepsilon}_m + (\bar{\varepsilon}_{\text{cut}} - \bar{\varepsilon}_m) L^{II}} \right] \]

\[ \bar{\varepsilon}_m = \varepsilon_0 \varepsilon_m - i \frac{\sigma_m}{\omega} \]
The DEP force on a dipole given by equation (8) [40]:

$$F_{\text{DEP}} = (\mathbf{p} \cdot \nabla)E$$

In summary, the dipole moment of a particle depends on the particle geometry, particle conductivity and permittivity, medium conductivity and permittivity, and the electric field signal (frequency and amplitude). The particle with a stronger dipole moment will respond faster to the subjected electric field.

In this article, we selectively deposited CNTs on Interdigitated Electrodes (IDE) using a simple and scalable process. The CNTs are extracted from an oxidized conductive carbon mixture that contains CNTs, spherical particles, and amorphous carbon. The process starts by functionalizing the mixture using a mild acid treatment to extract the CNTs and increasing their processability. The treated mixture is then dispersed in different solvents to investigate their solubility. Candidate solvents are used to assemble the CNTs on an electrode gap using an electrical force.

2. Materials and methods

2.1. Carbon powder treatments

The as-received carbon powder (Sample 0) was synthesized by chemical vapor deposition (CVD) using Fe nanoparticles as catalysts. The first sample (S1) was prepared by dispersing 300 mg of (S0) into 70 ml of nitric acid 3M HNO₃ (13.572 ml of commercial HNO₃ (70% w/w) added to 17.5 ml of DIW, then the volume was adjusted to 70 ml by DIW). The dispersion was mechanically stirred for 15 min at 60 °C, then sonicated in a conventional ultrasonic bath (100 W, 42 kHz) for 2 h. Ice cubes were placed in the ultrasonic bath to reduce the temperature and promote a less destructive process. The supernatant acid was discarded after centrifugation at 10000g for 15 min, and the remaining slurry was washed with DIW and distilled water until the pH was neutral (pH = 7). The slurry was moved into a 20 ml glass vial and dried on a hotplate at 150 °C for 12 h. The dried powder was then treated with hydrogen peroxide (H₂O₂) (30% v/v). The same procedure was repeated, except using H₂O₂ instead of HNO₃.

The second sample (S2) was prepared by mixing 5 ml of nitric acid 4M HNO₃ (3.185 ml of commercial HNO₃ (70% w/w R&M Chemicals) added to 1.25 ml DIW, then the final volume adjusted to 5 ml with DIW) and 15 ml of sulfuric acid 10M H₂SO₄ (8.416 ml of commercial H₂SO₄ (95.0% w/w R&M Chemicals) added to 3.75 ml DIW, then the final volume adjusted to 15 ml with DIW). A mass of 100 mg of S0 was dispersed into 20 ml of the acid mixture in a molar ratio of 1:3. The mixture was ultrasonicated for 30 min and then magnetically stirred for 5 h at 500 rpm and 30 °C. 10 ml of DIW was added to the mixture during the stirring process to mitigate the reaction and collect the CNTs that were attached to the Baker walls. A second acid mixture was added to regulate the oxidation process and reduce the concentration of nitrate and sulfate functional groups. The second mixture was 50 ml of hydrogen peroxide (30% v/v R&M Chemicals) and DIW with a ratio of 2:3. The ultrasonication process was repeated, and the mixture was centrifuged at 10000g for 15 min. The supernatant acid was discarded, and the treated slurry was washed using a washing cycle until pH measurement was neutral (pH = 7). The powder was dried in an oven at 80 °C for 20 h. Table 1 shows the identification code of each sample and the performed treatments.

| Sample code | Treatment                   |
|-------------|-----------------------------|
| S0          | As-received                 |
| S1          | HNO₃ + H₂O₂                  |
| S2          | HNO₃ + H₂O₂ + H₂SO₄         |

Table 1. Sample identification and performed treatments.
2.2. Dispersion in different solvents

The solubility degree of each sample can be investigated by uniformly dispersing the sample in a similar solution. 1 mg of each sample was placed in a vial containing 15 ml of ethanol. The dispersions were sonicated for 10 min at a temperature between 26 °C – 30 °C. Similarly, S1 was placed in 6 different vials containing different solvents at a concentration of 0.00667 wt%. The dispersions were sonicated for 10 min at room temperature (26 °C–30 °C). All dispersions were stored for a few weeks before characterization to allow large particles to sediment. Table 2 shows the mediums used to disperse the treated sample.

2.3. Selective deposition on IDE electrodes

The experimental setup of the assembly of CNTs using DEP force has three main components, as shown in figure 1. The first component is a transparent electrode fabricated on an ITO-coated glass substrate using conventional lithography. The electrodes have an interdigitated structure with finger-width and spacing of 100 μm and 50 μm, respectively. The electrode pads are connected to the second component, which is the source of the electric field. An AC generator was used to supply the system with an AC signal of 7.07 Vrms and 1 MHz. The last component is a drop of the CNTs solution (M6) was pipetted onto the electrodes. The electric field was turned on after the drop stabilized and kept on until the drop was thoroughly dried. The selective deposition of the carbon particles was observed and imaged using optical and electron microscopy.

3. Results and discussion

3.1. Treatments results

Several characterization techniques confirmed the quality of acid treatments. The presence of new functional groups on the surface of the treated samples was determined by Fourier-transform infrared spectroscopy (FTIR) (Perkin Elmer Spectrum 100), while the degree of defection was measured by Raman spectroscopy (WITec Alpha 300R). X-ray powder diffraction (XRD) was used to confirm the graphitic structure of the as-received sample. The changes in the surface morphology were observed by field-emission scanning electron microscope.

Table 2. Mediums that are used to investigate the dispersity and solubility of S1.

| Medium code | Solvent   | Formula |
|-------------|-----------|---------|
| M1          | Ethanol   | C₂H₆O   |
| M2          | DMF       | C₃H₇NO  |
| M3          | DCE       | C₂H₄Cl₂ |
| M4          | Toluene   | C₇H₈    |
| M5          | Acetone   | C₃H₆O   |
| M6          | DIW       | H₂O     |

Figure 1. Block diagram of the selective deposition mechanism. The figure shows the three main components of the DEP setup. (a) CNT/carbon mixture (medium). (b) AC signal source. (c) ITO-coated glass substrate. (d) Side view and top view of the complete DEP setup showing the CNT nanoparticles’ behavior when the AC generator is turned on.
The XRD pattern in figure 2(a) shows an intense diffraction peak at 2θ = 26°, which indicates that the sample has a highly graphitic structure. The three low peaks at 44°, 53°, and 78° are assigned to (100), (004), and (110) planes, which are patterns of typical graphite [41]. The absence of other peaks in the curve (except for 64°) indicates extremely low carbonaceous impurities and metal particles.

Raman spectra results are presented in figure 2(b). We observed a left shift in the functionalized samples in the D-band region and the G-band region (figure 2(b) inset). Although the shift was only 4 cm⁻¹, it can be explained as a release of CNTs from the carbon agglomerations to the sample surface. It can also be viewed as a change in particle size, as described by Costa et al [42]. The intensity ratio of amorphous/disordered carbon (sp3) relative to graphic carbon (sp2) (ID/IG) is calculated and also shown in figure 2(b). The ID/IG ratio indicates the degree of defects caused by the treatment process and the binding of new functional groups. The lowest ratio was found in S1, then S2, which suggests that the defects were reduced compared to the as-received sample. It can also be explained as an increase in the CNT density on the sample surface due to tube extraction during the treatments.

The FTIR spectrums of the treated and untreated samples are shown in figure 3. Sharp peaks were observed at wavenumbers (1370–1630 cm⁻¹) in all samples, which indicate the presence of the carbon π bonds (C=C) before and after treatments. The second peak was a broad absorption at 3200–3600 cm⁻¹ (O–H stretching). This hydroxide peak was higher and stronger in S1 and S2, which indicates an increase in the functional groups on the surface of the treated samples. The degree of the oxidation process was indicated by the strength of the carbonyl group C=O at (1714 cm⁻¹–1726 cm⁻¹). The carbonyl peak was also sharp in the as-received sample due to oxidation during synthesis. The oxidation intensity was high in S2 because the sample was treated with three...
different acids. In conclusion, the increase in the conjugated C=C absorption peak indicates mild treatment, and no over-functionalization occurred. The presence of hydroxyl groups (O–H/C–H and O–H/C=C) indicates that the samples were successfully functionalized.

The surface morphology of S0, S1 and S2 was characterized by FESEM and HRTEM imaging spectroscopy. The CNTs were implanted and trapped in S0 conglomerates, as shown in figures 4(a) and (d) (blue arrows), while amorphous carbon particles appeared in irregular shapes without any specific pattern. However, the conglomerates fragmented into smaller pieces after the treatments and the CNTs were extracted and clearly seen in S1 and S2, as shown in figures 4(b) and (c) (yellow arrows). The defection in the CNTs was two types: CNTs with different thicknesses at the ends observed in S1 and CNTs with open ends observed in S2 (figures 4(e) and (f) (red circle)). The presence of catalytic remains is also observed in the treated samples.

In conclusion, the treatment process helped extract and functionalize CNTs that were implanted and integrated into the carbon conglomerates. The acids penetrated the sample particles during the stirring and sonication phase and produced functional groups on the CNTs’ surface. The functional groups weaken the Van der Waals bonds and prevent agglomeration during the drying phase. There is no proof that treatments cause the defections; perhaps they already exist in the original sample. Figure 4(d) shows a CNT with open ends before the mild acid treatment (blue arrow).

The composition of the materials in each sample was obtained by conducting energy dispersive x-ray analysis (EDX) analysis. The percentage of each element in each sample is summarized in table 3. The presence of iron nanoparticles in S0 indicates that iron was used as a catalyst to synthesize the carbon powder. The oxygen ratio in S2 was slightly higher than that in S1 because the treatment time of S2 was longer than S1. The combination of nitric and sulfuric acid was more substantial than the nitric and hydrogen peroxide in eliminating the catalyst. However, mild acid treatment removed two-thirds of the catalytic particles in exchange for fewer surface defects.

In conclusion, the first treatment procedure was less harsh and introduced more functional groups on the CNTs’ surface.

| Element | S0     | S1     | S2     |
|---------|--------|--------|--------|
| C       | 88.43% | 94.3%  | 92.4%  |
| O       | 1.04%  | 2.3%   | 2.5%   |
| N       | —      | <1%    | <1%    |
| S       | —      | —      | 1.2%   |
| Fe      | 10.53% | 3.1%   | 3.8%   |

![Figure 4. FeSEM imaging of (a) S0. (b) S2. (c) S3. and TEM imaging of (d) S0. (e) S2. (f) S3.](image)
3.2. Dispersion results

CNTs tend to agglomerate and sediment in a polar solvent due to their strong inter-bonds and high surface energy. The attached functional groups on the CNTs' walls during the treatment create an electrostatic force due to their negative charges. This electrostatic force weakens the CNTs' strong inter-bonds, and hence the dispersion quality will depend on the charge volume. Ultraviolet-visible spectroscopy (UV-vis) (Perkin Elmer, Lambda 35), dynamic light scattering (DLS) (Malvern Instruments, Nano S), and agglomeration time were used to characterize the CNTs' dispersions in terms of solubility and stability.

The particle size distribution of all samples was obtained using DLS analysis, as shown in figure 5. The intensity of the scattered light from S0 has a peak at 300 nm. The intensity peak was dropped to 200 nm in the treated samples due to the solubility enhancement after acid functionalization (figure 5(a)). There are no differences between the two treatments, except a slight shift to the left in S1, indicating smaller particles. The volume distribution of the samples is shown in figure 5(b). The particle sizes for the treated samples were distributed in two size ranges (60 nm–600 nm) and (3000 nm–7000 nm). For the untreated sample, the size distribution was in the range of (80 nm–1500 nm) and (3000 nm–6500 nm). The size reduction at the low range indicates that the CNTs successfully functionalized, and their dispersity was improved.

The medium with high UV-vis absorbance indicates good dispersity. The degree of solubility can be determined by the solute, solvent or both. To investigate the solute’s role, S0, S1, and S2 were dispersed in ethanol (M1). The absorbance curve and the dispersed samples are shown in figure 6(a). The UV-vis measurements were taken three weeks after preparing the medium to ensure medium stability. No absorbance peak was observed in S0 in either concentration (1 mg and 2 mg). The untreated sample suffers from low dispersity due to the absence of functional groups. The peak at the wavelength of 260 nm confirms the presence...
of individual CNTs in S1 and S2. However, S1 showed a higher peak and hence was selected as the best solute and used to investigate the solvent quality.

Solvent quality was studied by dispersing S1 in six different solvents. The results are shown in figure 6(b). The non-bonding to π anti-bonding absorption peaks at 290 nm is present in toluene and acetone. Ethanol and DIW have a stable absorption line through the wavelength range, while DMF shows a higher and more stable absorbance than any other solvent. DCE was the only solvent with a small broad peak at 260 nm. The visual observation of the agglomeration time matches with the UV-vis absorbance values of the six solutions.

The time CNTs take to agglomerate and sediment can provide qualitative information about the dispersion quality. The inset picture in figure 6(b) shows the stability of the CNTs in solvents M1 to M6. The picture was taken two months after the samples were prepared. DIW and acetone showed higher stability where CNTs did not aggregate after this long period. The lowest stability was observed in toluene, then DCE, as the CNTs sediment after a few hours. In general, DIW and ethanol are preferred in terms of dispersity, while DMF and acetone are better in terms of stability. The medium compatibility with the electrode materials and the medium’s evaporation speed is also considered when choosing a proper solvent.

3.3. Selective deposition results

The selective deposition principle is that particles with different conductivity and permittivity behave differently under the same electric field. The particle size and shape also contribute to the dipole moment value. Besides the particle’s properties and dimensions, three other factors control the selective deposition: the electrode geometry, the medium, and the parameters of the supplied AC signal. IDE configuration was chosen because it is widely used for several electronic applications, such as sensors. Based on the results from the previous section, we have selected DIW and DMF as mediums. Ethanol and acetone showed strong solubility and dispersity of CNTs, but their high evaporation rate made them unsuitable for the assembly of CNTs across wide electrode gaps. We have used a slightly high potential of 7.07 Vrms because the spacing between the electrode fingers is 50 μm. The relatively high frequency is to reduce any side forces, such as the electroosmotic force that exists at lower frequencies.

The DEP force exerted on a CNT and the resulting CNT velocity are shown in figure 7(a). The k factor and polarizability factor values in the figure were obtained from equations (3)–(4). The force and velocity are at maximum values at the electrode edges (25 μm) and minimum values at the gap centre (0 μm). The force and velocity variation explain the instant deposition of CNTs at the edges, and the last location filled with CNTs is the gap centre (figures 7(c) and (d)). The deposition continues as long as the AC signal is still on until the target density is obtained (figures 7(e) and (f)). The particles with low polarizability will remain in the medium and can be collected on the ITO surface near the edge after the medium dries up. Figures 7(e) and (f) show the differences in using DIW and DMF as solvents. The formed connections were thicker in the case of DIW, with larger spacing between each connection, while in the case of DMF, the connections were thinner and closer to each other. The thicker connection means that the CNTs re-bundled faster in DIW, making DMF more preferable than DIW at a wider electrode gap. The high surface tension of DIW (72.80 mN m⁻¹) compared with DMF (36.70 mN m⁻¹) was responsible for distorting the deposited network upon drying (figure 7(e)).
Figure 8. FESEM image of the deposited CNTs and amorphous carbon from a DIW solution.

Figure 9. Selective deposition of CNT from a mixture of CNT and PS particles suspended in DIW. (a) AC signal off. (b) 3 min after applying an AC signal of 7.07 Vrms and frequency of 1 MHz. (Supplementary Video2: the video demonstrates the assembly of CNTs from a DIW that contains a mixture of CNTs and PS particles in real-time).

Figure 10. The resistance of the deposited CNT versus deposition time. The inset shows the resistance versus time up to 10 min.
The FESEM imaging of the deposited CNTs is shown in figure 8. CNTs and small spherical carbon particles were deposited at the electrode gap because DEP force tends to move the particles into the region with a high electric field. The CNTs tended to align with the electric field lines; however, some particles agglutinated the surface of the CNTs, preventing them from moving freely. On the other hand, large particles and amorphous carbon accumulated on the ITO electrodes’ edges. The accumulation occurred due to the presence of the AC Electrohydrodynamic (AC EHD) effect, which dominates the DEP for particles with low polarizability and tends to trap them on the electrode surface.

The selective deposition was successfully conducted using a simple low-power procedure. There is room for improvement in terms of the medium dispersity to avoid the deposition of small spherical particles that obstruct the CNTs from being fully aligned. A wider electrode gap might be used with suitable potential to increase the improvement in terms of the medium dispersity to avoid the deposition of small spherical particles that obstruct the CNTs from being fully aligned. A wider electrode gap might be used with suitable potential to increase the deposition yield.

The selective deposition of CNTs from a mixture that contains non-carbon particles such as polystyrene (PS) particles is demonstrated. The carbon mixture solution is replaced with a solution that contains pure CNTs and PS particles (PP-30–10, Spherotech). Figure 9(a) shows PS particles randomly distributed in a droplet placed on the electrodes while CNTs are not visible due to their small size. To selectively deposit CNTs on the electrode gaps, the frequency of the AC signal is set to 1 MHz. CNTs are started to form connections across the electrode gaps once the AC signal is turned on, as shown in figure 9(b). The density of the CNT connections increases over time. At 1 MHz, PS particles experience negative DEP force due to their low electrical conductivity, and thus they are moved toward regions with low electric fields (far from the electrode gaps).

Figure 10 shows the resistance of the deposited CNTs as a function of the deposition time. The resistance dropped to the kilo-ohm range in the first minute, indicating the formation of CNT connections across the electrodes. The resistance continues to decrease as the density of the deposited CNTs increases over time. The deposition time is not the only factor that determines the resistance of the assembled CNTs. Other factors, such as the concentration of CNTs in the solution, AC signal amplitude and annealing after the assembly, are also significant in determining the resistance of the deposited CNTs. For example, at an AC signal of 5.30 Vrms, the resistance of the deposited CNTs after 10 min was 13.6 kΩ compared to a resistance of 9.3 kΩ at 7.07 Vrms. The resistance dropped to below 5 kΩ after annealing the deposited CNTs at a temperature of 100 °C for 1 h. The resistance curves in figure 10 are for CNTs deposited from DIW. However, no significant effect on the total resistance in the case of using DMF solvent instead of DIW.

4. Conclusions

Synthesized CNTs may contain pyramidal and spherical structures along with the tubular structure, which happens at less demanding or below the optimum growth conditions. DEP is a phenomenon utilized to manipulate particles due to its simplicity and low cost. The method can be used to sort, extract and process particles located among a mixture or a variety of other particles. In this article, we employed DEP to deposit CNTs selectively from a synthesized carbon mixture. Before the deposition, the CNTs sample underwent treatment and dispersion procedures to increase their processability and solubility. We relied on a mild acid treatment to preserve the CNTs’ electric properties and to minimize defections. The mild treatments included low concentration acids, low sonication power and low-temperature media. The treatment and dispersion quality were confirmed by several characterization techniques, including FTIR, Raman, DLS, UV-vis, HRTEM and EDX. The structure of the deposited CNTs and amorphous carbon was imaged with an optical microscope in real-time and confirmed by FESEM microscopy. The selective deposition of CNTs can be employed in sensors where a high-sensitivity material can be deposited on electrode structure. The method has the potential to be employed in microfluidic systems for real-time continuous separation of nanoparticles. The selective deposition approach investigated in this article can be applied to other nanoparticles and can be extended to multi-level depositions, where a different particle can be deposited at different electric parameters (multi-layer deposition). The method can also replace the methods where the sorted particles require a transfer step to the target location.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).
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Conflicts of Interest

The authors declare no conflict of interest.

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