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CNT thin films based on epoxy mixtures: fabrication, electrical characteristics

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Abstract

The simple scaling of silicon transistors no longer ensures the advantages of high energy efficiency, driving research into nanotechnologies beyond silicon. Specifically, digital circuits based on carbon nanotube (CNT) field-effect transistors promise significant advantages in energy efficiency. However, the inability to perfectly control internal nanoscale defects and the variability of carbon nanotubes hinder the realization of very large-scale integrated systems. In this study, we investigated a novel method for fabricating transistors based on carbon nanotubes (CNTs) using epoxy mixtures, obtained the electrical properties of the transistors, and compared their microstructure and composition via the scanning electron microscopy. The carrier mobility on epoxy-based transistors was 28.87 cm^2/V·s, and the transistor switching frequency was 2.2 MHz. The samples exhibited electrical and physical stability over an extended period of time. The use of carbon nanotubes in epoxy resin as a conducting layer for transistors opens significant prospects in the field of electronics. The CNT-epoxy mixture technology allows for more flexible and rapid fabrication of thin-film transistors compared to classical methods. However, it is not appropriate to speak of a complete replacement; in this study, we present an alternative method for producing thin-film transistors, which may be of interest for specific purposes.

Keywords

carbon nanotubes
epoxy mixtures
thin films
transistors
organic electronics

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Key findings

- An alternative method for producing thin-film transistors was presented.
- The carrier mobility was 28.87 cm^2/V·s, and the transistor switching frequency was 2.2 MHz.
- CNT-epoxy mixtures have potential for thin-film device production, but require improved dispersion and film deposition methods.

1. Introduction

The exploration of carbon nanotubes (CNTs) and their applications has been a subject of extensive research within the scientific community. Various literature sources have highlighted the unique properties and potential applications of CNTs, providing a comprehensive understanding of their synthesis, characterization, and utilization in diverse fields.

1.1. Mechanical, electrical, and functional properties of CNTs

Initial studies on these materials have focused on elucidating their mechanical, electrical, and functional properties. Researchers have extensively documented the exceptional strength, flexibility, and electrical conductivity [1–4]. These properties were attributed to the unique structure of CNTs, consisting of rolled-up graphene sheets with sp^2 hybridized carbon atoms. This structural arrangement allows for efficient electron transport along the length of the nanotube, leading to high electrical conductivity [5–9]. Furthermore, the hollow cylindrical structure of CNTs contributes to their exceptional mechanical properties, making them ideal candidates for reinforcement in composite materials [1, 6–9].

1.2. Synthesis and characterization techniques

The synthesis of CNTs has been a subject of significant interest, with researchers developing various methods to produce nanotubes with specific properties [10, 11]. Literature reviews have extensively covered techniques such as arc discharge, chemical vapor deposition (CVD), and laser ablation for the synthesis of CNTs [12–13]. Additionally, characterization techniques such as transmission electron microscopy (TEM), scanning electron microscopy (SEM), and Raman spectroscopy have been employed to analyze the structure, morphology, and purity of samples [1, 2, 14]. These techniques play a crucial role in understanding the growth mechanisms and properties of CNTs, facilitating their integration into various applications.

1.3. Applications of CNTs in composite materials

The utilization of CNTs in composite materials has garnered considerable attention due to their ability to impart enhanced mechanical, electrical, and thermal properties. Literature sources have extensively discussed the incorporation of carbon nanotubes into polymer matrices to develop nanocomposites with improved strength, stiffness, and electrical conductivity [9]. Additionally, studies have explored the use of this materials as fillers in metal and ceramic matrices to enhance the mechanical and thermal properties of composites [11, 15–17]. These applications highlight the versatility of CNTs in reinforcing various materials and their potential impact on industries such as aerospace, automotive, and electronics.

1.4. Challenges and future directions

Despite the promising properties of CNTs, their widespread commercialization faces challenges related to scalability, cost-effectiveness, and environmental impact. Literature sources have addressed these challenges and proposed strategies to overcome them, including the development of scalable synthesis methods, functionalization techniques to improve compatibility with matrices, and recycling processes to mitigate environmental concerns [12, 13, 18]. Furthermore, ongoing research aims to explore novel applications of CNTs in emerging fields such as energy storage, biomedicine, and environmental remediation, indicating the continued relevance and potential of these nanomaterials [19–21].

1.5. CNT/epoxy-masterbatch based nanocomposites

Traditionally, CNT-epoxy mixtures have been explored for various purposes. They offer a promising combination of mechanical support from the epoxy and the unique electrical properties of carbon nanotubes [22–23]. This synergy can be harnessed in applications like conductive adhesives, shielding materials, and even structural components for electronic devices [8, 25–27].

Having experience working with CNTs to create nanocomposite materials, we can find areas of application of CNTs in electronics [28–30]. This study extends the exploration initiated in a previous study in the development of nanocomposite thin film structures utilizing poly-arylenephthalide matrices with single-walled carbon nanotubes (SWCNT) and graphene oxide fillers [31]. It builds upon the advancements in hybrid molecular systems reported elsewhere, particularly in the synthesis of hybrid molecules incorporating fullerene C60 and dithienylethenes for optically controlled organic field-effect transistors (OFETs) [32]. Furthermore, it draws inspiration from optically controlled OFETs described in other studies utilizing photochromic spiropyran and fullerene C60 films [33–34]. These investigations lay the groundwork for our current endeavor, which focuses on the integration of carbon nanotubes within epoxy matrices to elucidate their combined effects on electrical conductivity and transistor performance in organic thin-film transistors (OTFTs). In doing so, we aim to contribute to the ongoing exploration of electrical properties in polymer films and heterostructure materials, as previously investigated elsewhere [35–36]. Our study aspires to unravel the intricate interplay between CNT dispersion, charge transfer mechanisms, and film morphology within the context of OTFTs, thereby advancing the development of next-generation functional materials for organic electronics.

2. Materials and Methods

2.1. CNT thin films: substrate preparation, SEM, EDX

Crystalline silicon substrates with an aluminum oxide sublayer were employed for thin film deposition. The substrates were chemically cleaned with acetone to remove organic contaminants and then placed in a vacuum installation to avoid further contamination and the deposition of dust particles on them.

The growth of carbon nanotubes on the silicon substrate with iron catalyst was achieved via chemical vapor deposition (CVD). The process involved the formation of nanosized iron droplets on the substrate surface, followed by the pyrolysis of ethylene at 600 °C in an argon atmosphere for 7 min. Self-organized nanodroplets acted as catalysts for the growth of multi-walled CNT arrays.

On top of the layer of nanotubes, contact pads made of aluminum were deposited by thermal vacuum deposition. Since the technological process requires high accuracy and purity of the components, scanning electron microscopy (SEM) of the samples was carried out, and their elemental composition was studied using energy dispersive X-ray spectroscopy (EDX). The study was carried out on a Tescan Mira electron microscope with an installed spectrometer module.

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Parameters such as deposition rate and substrate temperature were adjusted to control the structure and properties of the CNT thin film. SEM imaging and EDX analysis aided in evaluating the film's structural integrity and purity.

Spectral analysis was conducted using SEM and EDX to assess the purity of the samples and identify the distribution of elements within the CNT layer. The studies were carried out in the Oxford Instruments AZtec system. Preliminary preparation of the samples was not required, since they already met the requirements: a flat and well-polished coating, no contamination.

Current-voltage characteristics were measured to evaluate the electrical behavior of the carbon layer over time. Stability assessments were conducted to examine the resistance to mechanical and environmental factors.

Various post-treatment techniques such as heat treatment, laser irradiation, and chemical functionalization were explored to modify the structure and properties of the CNT thin film.

2.2. CNT-Epoxy: fabrication, electrical properties, SEM

Obtaining a mixture of CNTs and epoxy resin consists of several stages, each of which plays an important role in the final result. To begin with, it is necessary to carry out calculations of the required concentrations of substances to obtain the required level of conductivity. Depending on the manufacturer of both the CNT and epoxy resin, the ratios of the substances may vary. In our case, the concentration of single-walled CNTs in the mixture was ~0.3% of the total mass, which made it possible to achieve currents of the order of 150–800 μA at drain-source voltages from 2 to 12 V. Theoretical data and the results of other works indicate currents of ~120 μA at a voltage of 12 V [29]. In general, the calculations and experimentally obtained data agree with each other within certain error margins, which will be discussed in more detail below.

To reduce the concentration of single-walled CNTs (SWCNTs), the masterbatch was diluted with an epoxy resin like the masterbatch base by shear mixing. For better dispersion, the viscosity of the mixture was lowered with acetone, which was subsequently removed during the degassing step. For degassing, the mixture was placed in a low-pressure chamber for a period of 30–60 min. Since the epoxy used was a two-component epoxy, the hardener was added at the last step. CNT masterbatch was mixed with epoxy by shear mixing for the desired 0.3 wt.% of CNTs at temperature of 45 °C and relative humidity of 30%.

The process of preparing the mixture before applying it to the substrate consisted of several stages. Three different mixing steps were utilized with varying speeds as demonstrated in Table 1. Low vacuum of 0.1 mbar was applied for 15 min in step 2 and step 3 to reduce air bubbles entrapment in the mixture. The masterbatch, epoxy, and hardener mixture were isotropic and homogeneous, and they will be further referred to as "CNT mixture" [30]. In step 4, the CNT mixture was mixed with acetone at low speed to obtain the final mixture ready for spin coating. The obtained mixture was spin coated on the substrate at varying high rpm speed (2000–5000 rpm) and subsequently degassed for 30–60 min to remove the acetone.

The mixture obtained by this method is ready for application to the substrate by spin coating or pressing methods.

Three methods were employed for producing CNT-epoxy thin films: pressing, spreading, and drop casting. Each method offered distinct advantages in terms of simplicity, uniformity, and film thickness control.

Scanning electron microscopy was utilized to capture surface images of the CNT-epoxy mixture and thin-film structures. The images were analyzed to assess dispersion uniformity and structural characteristics.

The active layer of the transistor was obtained using the drop casting method. The method made it possible to obtain the required conductivity layer in the channel in the simplest way. Glass coated with indium tin oxide (ITO) was used as the substrate material. As a gate dielectric, an AlOX solution was applied on a centrifuge, followed by heating in an oven (60 minutes). The contact pads were obtained by thermal spraying of aluminum in a vacuum.

The electrical properties of the transistors were characterized through current-voltage measurements. Mobility calculations were performed using established formulas, and switching frequency was determined based on the obtained electrical parameters.

The methods outlined above provide a comprehensive approach to the production and characterization of CNT thin films. These techniques offer flexibility in controlling film structure and properties, with potential applications in various electronic devices and sensors. Further research is warranted to optimize production processes and explore additional applications of CNT-epoxy mixtures.

3. CNT thin films

Obtaining a uniform layer of carbon nanotubes on large surfaces is a difficult task. By solving this problem, you can get a lot of scalable functional devices, for example, scanning probes and sensors, field emitters and nanoelectronics elements [16, 37].

Table 1 Steps for mixing masterbatch with epoxy.

Materials	Step 1	Step 2	
Masterbatch + Epoxy	Low speed heating (45 C, 20 min)	High speed heating (45 C, 60 min)	15 min vacuum
	Step 3		
Masterbatch + Epoxy + Hardener	Low speed Without heating (20 min)		15 min vacuum
	Step 4		
CNT mixture + Acetone	Low speed Without heating (20 min)	Spin coating on substrate	30–60 min vacuum

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Significant effort is required to create useful structures in order to deposit nanotubes in a controlled manner without additional manipulation or assembly after they have been deposited. A carbon layer over a silicon substrate can be obtained by synthesizing CNTs on its surface [2, 38]. The morphology of the carbon layer is shown in Figure 1. The SEM method can be used to evaluate surface morphology such as roughness, dispersion uniformity of nanomaterials. Simple sample preparation and simple image understanding make SEM the most common electron microscopy method for this purpose.

It can be seen from the images obtained that CNTs have a high curvature and form coils; however, their structure is not disturbed, which indicates a high-quality technology for their deposition. This is largely due to the choice of silicon substrate. It is known that a smooth silicon substrate makes it possible to obtain a high-quality CNT layer; moreover, silicon provides a good contrast in SEM observations [39–40]. When thin CNT films are deposited on a substrate, their structure can be controlled using various process parameters. One of these parameters is the deposition rate, which can affect the structure and properties of the film. A high sputtering rate can lead to the formation of shorter and more disordered CNTs, while a lower sputtering rate can promote the formation of longer and more ordered structures. Another important parameter is the temperature of the substrate during the spraying process. High temperature can promote more efficient growth and orientation of CNTs on the substrate. However, too high a temperature can cause defects in the film structure and even destruction of CNTs. It is also possible to use various film post-treatment techniques such as heat treatment, laser irradiation, or chemical functionalization to change the structure and properties of the CNT thin film.

Let us pay attention to the spectral analysis of chemical elements (Figure 2). Basically, the scanning electron microscopy supplied with the EDX is used to qualitatively and quantitatively analyze the elements present in a selected area of the SEM image to evaluate the content of metals and impurities in CNTs.

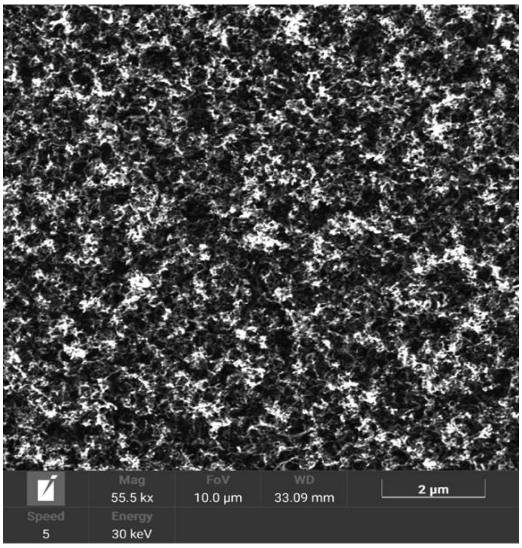

Figure 1 SEM image of CNTs grown on a substrate.

Using the capabilities of SEM, it is possible to perform focused electron beam irradiation, visualization of secondary or backscattered electrons, and energy analysis of X-rays.

The data obtained show that the samples have a high degree of purity, i.e., only the carbon layer is involved in the conduction mechanism. Also, carbon, having a minimal effect on the X-ray intensity during microanalysis, made it possible to dispense with applying a thin conductive layer on top of the samples.

From the spectral analysis shown in Figure 3, it can be seen that silicon occupies the bulk of the volume. Carbon, which has a relatively low concentration, gives a high degree of conductivity, which indicates its high structuring, which is typical for CNTs.

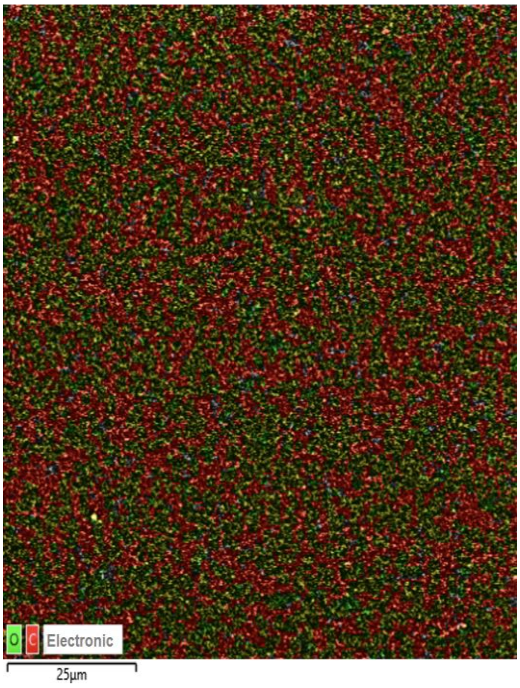

Figure 2 An image obtained by EDX showing the distribution of elements on the surface of a sample. The image was obtained by scanning the surface of a silicon wafer with MWCNTs.

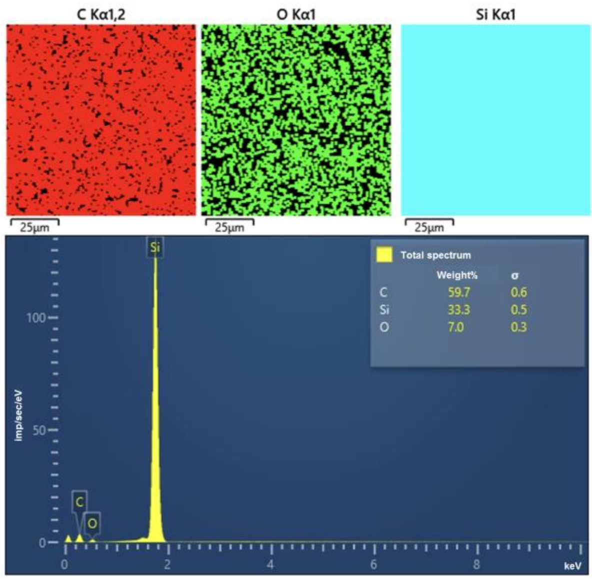

Figure 3 The elemental surface image obtained by chemical analysis shows the distribution of each element on the sample.

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The results of chemical analysis show that silicon occupies the largest volume on the substrate. This is due to the fact that during chemical analysis, radiation penetrates into the sample under study to a depth much greater than the thickness of the carbon layer.

Current-voltage characteristics expectedly showed that the carbon layer exhibits stable electrical behavior at various drain-source voltages, the repeatability of the data is confirmed by the measurements after 2 months, which indicates mechanical and environmental resistance and correlates with the studies of other groups [41–42]. Such behavior is beneficial when the fabricated devices are used, for example, in sensors or low-power solutions [43]. The stability advantage of CNTs over organic polymers is also worth noting. For example, polyanilines tend to oxidize and degrade over time, and can also lose sensitivity after several working iterations, which was proven in our previous studies, although the synthesis of organics is much simpler.

As can be seen, the production of thin films by vacuum deposition has a significant advantage in uniformity, purity, and also in the flexibility of controlling the structure of the CNT layer. However, this method is expensive and requires much more sophisticated equipment compared to the epoxy mixture method. This can be decisive in applications where high purity is not required and low cost is important at high production volumes.

4. CNT-Epoxy mixture

CNTs, depending on the chirality and quality of the production process, have a wide range of electrical conductivities, from semiconductor to metallic. High metallic conductivity is not always necessary when creating electronic components. In particular, for transistors, the conductivity level of semiconductors is optimal, the adequate degree of conductivity of which should correspond, for example, to the specific electrical conductivity of silicon, $4.35\ 10^{-4}$ S/m. The separation of CNTs according to their conductivity is a complex scientific and technical problem. Therefore, today it is easier to achieve semiconductor conductivity based on mixtures of CNTs with semiconducting or insulating materials, which make it easy to vary the effective conductivity of the mixture by changing the concentration of CNTs in it.

As a rule, CNTs in epoxy mixtures are used to create composite materials, and their mechanical properties are first studied [28]. However, the use of epoxy resin with CNT masterbatch allows to find potentially new areas of application for these mixtures. Mixtures of CNTs and epoxy resins have a controlled level of conductivity, which depends mainly on the concentrations of CNTs in the mixture. This mixture, according to physical properties, is also suitable for the synthesis of thin-film structures, although it imposes certain restrictions on the process of their preparation. The combination of these facts makes it possible to use CNTs based on epoxy mixtures to create thin-film electronic components.

Methods for producing thin films from epoxy mixtures differ from standard methods such as vacuum deposition or growing a carbon forest. Due to the fact that the mixture of CNTs and epoxy resin has a phase close to liquid, it is more convenient to use simpler and cheaper methods for producing thin films. The most successful methods are described below.

A drop of the mixture is applied to the surface, usually with a syringe. The droplet size varies depending on the size of the gate and the methods of its further distribution.

- Pressing. A drop applied to the surface is pressed evenly and tightly with a flat plate, as a result of which the mixture is distributed over the entire surface area (Figure 4a). After lifting the pressure plate, some displacement of the mixture is possible; however, as experiments have shown, this does not affect the electrical properties since the conductive layer remains unchanged.

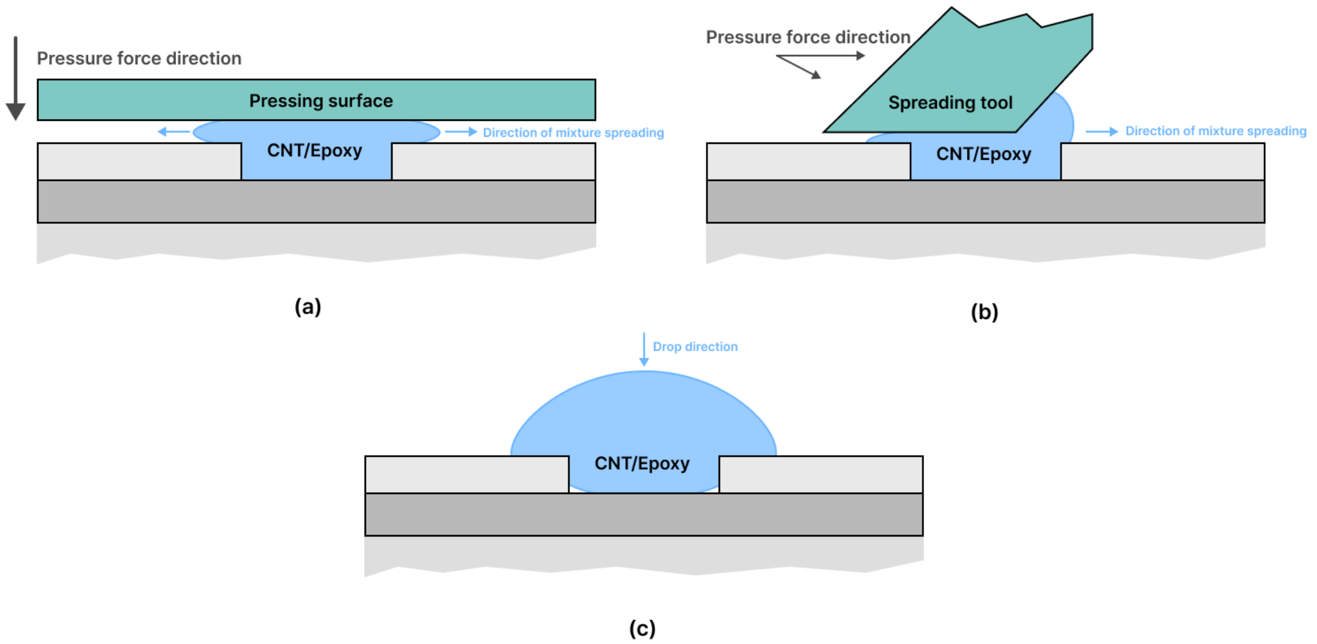

Figure 4 Mixture application methods: pressing method (a), spreading method (b), drop casting method (c).

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- Spreading method. The applied droplet is spread over the surface using a flat plate with a fixed controlled pressure, which ensures an even distribution of the mixture over the substrate. This method, although simple, produces a film thickness of about 10 μm with desirable electrical and mechanical stability. Unlike pressing, this method allows removing the pressing plate without the formation of concentrated "peaks" of the mixture as a result of its adhesion, due to which the entire area of the applied mixture has an almost uniform structure.
- Drop casting method. The drop method with a drying unit at high temperature (drop casting) (Figure 4c). A small drop (1–3 mm in diameter) is applied to the substrate in a solution with acetone, which allows increasing the fluidity of the solution at the time of application. Next, the sample is placed in an oven at sufficient temperature to slowly evaporate the acetone, where due to the evaporation of the solution, the film thickness reaches up to ten micrometers.

Regardless of the production methods, the films had long-term mechanical and electrical stability, since the main task was the formation of a conductive channel between the contact pads. However, drop casting method turned out to be the simplest method in terms of repeatability of results and ease of use. In this way, several samples of thin-film transistors were obtained. The channel width is ≈50 μm with a length of 5 mm, and the film thickness is ~10 μm, depending on the deposition method.

4.1. SEM

Several surface images of CNT-Epoxy were captured using a scanning electron microscope (Figure 5). The mixture was applied using the drop-casting method. The images depict areas with varying dispersion of the mixture: on the left – non-uniform dispersion, on the right – uniform dispersion. This discrepancy is attributed to the dispersion mechanisms of carbon nanotubes in the epoxy mixture, leading to the formation of agglomerations with elevated and reduced concentrations. Compared with the films obtained via the classical growth of CNT on a substrate, as illustrated in the previous images, the mixtures provide a structure that is not as clean and uniform. However, the latter thin-film structures were obtained by a significantly faster and simpler method.

The methods described above are laboratory methods with certain assumptions. It is obvious that for a full production cycle it is necessary to carry out work towards obtaining more homogeneous mixtures, as well as improving methods for applying films. However, the results already obtained allow us to say that this direction has the scalability potential.

5. CNT-Epoxy transistor

A thin film transistor based on CNT-Epoxy was obtained. Glass coated with ITO was used as the substrate material. As a gate dielectric, an AlO_X solution was applied with a thickness of 100 nm. The contact pads were made of aluminum. The structure of the resulting transistor is shown in Figure 6.

The current-voltage characteristics of the obtained transistors are shown in Figure 7. The measurement of their electrical properties showed that they have a high degree of conductivity of the order of hundreds of microamperes, which agrees with the studies from other groups [44–45].

The degree of conductivity can be adjusted by increasing or decreasing the concentration of epoxy in the mixture. As mentioned above, the concentration of CNTs in the mixture was ≈0.3% of the total mass. The required concentrations of the components can be theoretically calculated in advance; however, to do this, it is necessary to take into account the electrical properties of the EM from a specific manufacturer and batch and make the required adjustments to the calculations. These transistors based on thin films are in demand in sensors or smart devices, in which energy efficiency and overall dimensions with flexible properties are important [46–47].

Mobility calculations based on current-voltage characteristics were also carried out. The calculation was made according to Equation 1,

$$\mu = \frac{I_{DS}}{\frac{W}{L} \cdot C \cdot (V_G - V_{th}) \cdot V_{DS}}, \quad (1)$$

where I_{DS} is the drain-source current, W is the shutter width, L is the shutter length, C is the film capacity, V_G is the gate voltage, V_{th} is the threshold voltage, V_{DS} is the drain-source voltage.

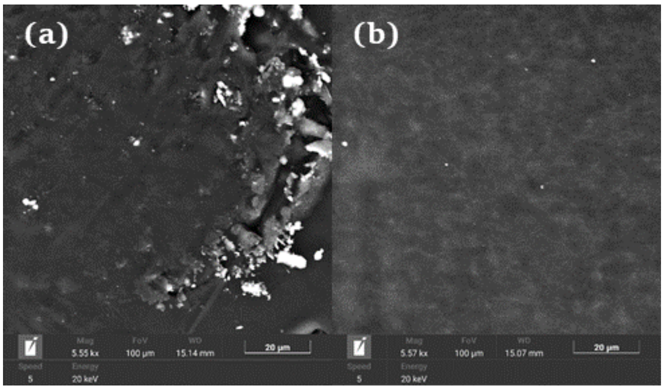

Figure 5 SEM image of CNT-Epoxy mixture: zone of non-uniform dispersion (a), zone of uniform dispersion (b).

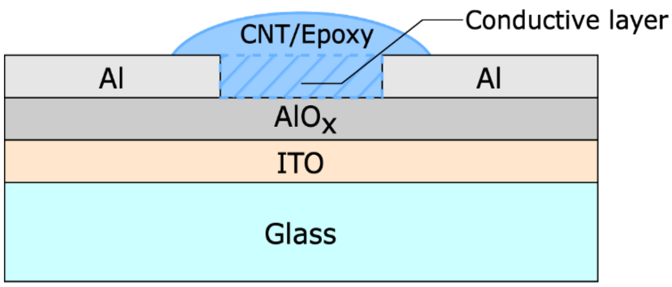

Figure 6 Structure of a thin film transistor based on an epoxy mixture of CNTs.

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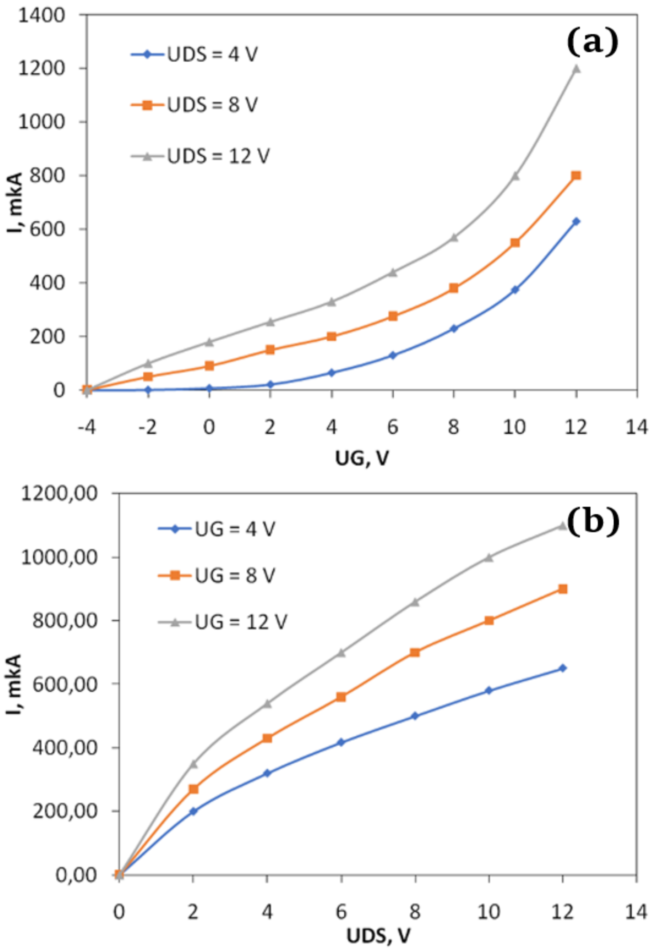

Figure 7 Output (a) and transfer (b) characteristics of an epoxy blended CNT transistor.

The calculated mobility μ was 28.87 $cm^2/V \cdot s$, at $V_{DS} = 12$ V, $C = 8.9 \cdot 10^{-9}$ F/cm^2, $L = 50 \cdot 10^{-4}$ cm, $W = 2 \cdot 10^{-1}$ cm, $V_{DS} = 12$V, $V_G = 12$ V, $V_{th} = 6$ V, $I_{DS} = 740 \cdot 10^{-6}$ A.

The calculation of the switching frequency of the transistor (Equation 2) showed a frequency of 2.2 MHz with the same input data. High frequencies are due to high conductivity and mobility.

$$f = \frac{1}{2\pi} \frac{\mu V_{DS}}{L^2} \quad (2)$$

It should be noted that different samples showed different results due to several factors. First, in addition to the concentration of CNTs, the structure of the mixture also plays an important role in the conduction mechanism. It was experimentally found that a high degree of dispersion homogeneity gives a higher conductivity value. A closer arrangement of CNT agglomerates, as well as their uniformity, leads to lower electrical resistivity values. Secondly, the quality of production and the method of processing masterbatches, as well as their dilution, affect the final electrical resistivity of the produced materials. It was also found that in combination with efficient industrial dispersion (three-roll mill) and chemical compounds in the production of the masterbatch, the degree of dispersion of the tubes in the precursor is much higher, which allows for better final dispersion of the nanotubes as well as a smaller agglomerate size. Due to their geometric characteristics, denser networks form single-walled CNTs, the degree of conductivity of which exceeds multi-walled CNTs by several orders of magnitude. Thus, particle geometry, degree of dispersion, distances between particles and agglomeration in CNT epoxy mixtures directly affect the conductivity; therefore, in order to obtain stable and uniform thin films in which high accuracy in currents is required, it is necessary to carefully monitor the technological process or expect significant percentage of defective devices.

Features of CNT dispersion and film deposition cause some differences in electrical properties between samples. In addition to the concentration of CNTs, the structure of the mixture plays a significant role in the conduction mechanism. An important role is played by the quality of production and the method of processing masterbatches and their dilution.

Nevertheless, the results obtained show a high degree of film conductivity even after a long time (3 months), which indicates the stability of the composition and the absence of film degradation. Based on experience of using CNTs in metal matrix composites, one can expect stability of operation up to high temperatures of several hundred degrees Celsius, taking into account the complex behavior of the temperature coefficient of electrical resistance.

There are several ways to control the electrical properties of CNTs in epoxy resin. One of them is the addition of functional groups to the CNT surface, which can change their surface properties and interaction with the epoxy resin. Another way is to change the concentration of CNTs in the epoxy resin. It is also possible to use additional components such as metal nanoparticles or polymer additives to control the electrical properties of the CNTs in the epoxy resin. However, each of these methods has its limitations and requires further research. For example, in some papers explore various ways to functionalize CNTs to improve dispersion and interfacial interaction in epoxy composites [37]. Also, some groups investigate the effect of CNT concentration on electrical conductivity and mechanical properties of CNT-epoxy composites [48].

It is worth noting that carbon nanotubes (CNTs) are utilized in certain methods for detecting hydrocarbons, acting as sensors [49–51]. CNTs possess a large surface area and unique electronic properties that enable them to detect small quantities of hydrocarbons in the surrounding environment. Several approaches exist for employing CNTs as hydrocarbon sensors. One such approach involves using CNTs as elements in field-effect transistors. CNTs are incorporated into the transistor material and utilized for the detection of hydrocarbons. Another approach involves using CNTs as a material for electrochemical sensors. In this case, CNTs are coated with a polymer layer exhibiting high selectivity towards hydrocarbons, allowing the detection of even low concentrations in the surrounding environment. Thus, there is potential for the application of CNT-epoxy mixtures as hydrocarbon sensors; however, this necessitates further research.

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6. Conclusion

The resulting thin-film structures comprising carbon nanotubes (CNTs) and epoxy mixtures exhibit promise for applications in film electronics, albeit with the caveat of necessitating enhanced fabrication techniques. The intricacies of CNT dissolution within epoxy resins and the methods employed for film deposition do not consistently yield reproducible outcomes. These processes may give rise to clusters with varying concentrations of CNTs, thereby engendering electrical disparities across different samples, typically within a margin of 5–7% from the calculated mobility of 28.87 cm^2/V·s. The transistor switching frequency, averaging 2.2 MHz across all samples with a spread of values falling within the 10–15% range, correlates with the divergence in cluster structures among samples. Despite these variations, all samples exhibited stable electrical properties even after prolonged exposure to ambient conditions, manifesting no signs of degradation or detrimental effects on thin-film characteristics.

● Supplementary materials

No supplementary materials are available.

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● Conflict of interest

The authors declare no conflict of interest.

● Additional information

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Skolkovo Institute of Science and Technology, https://new.skoltech.ru/en/.

References

1. Soni SK, Thomas B, Kar VR. A comprehensive review on CNTs and CNT-reinforced composites: syntheses, characteristics and applications. Mater Today Commun. 2020;25:101546. doi:10.1016/j.mtcomm.2020.101546
2. Rathinavel S, Priyadharshini K, Panda D. A review on carbon nanotube: An overview of synthesis, properties, functionalization, characterization, and the application. Mater Sci Eng B Adv. 2021;268:115095. doi:10.1016/j.mseb.2021.115095
3. Hills G, Lau C, Wright A, Fuller S, Bishop MD, Srimani T, Shulaker MM. Modern microprocessor built from complementary carbon nanotube transistors. Nature. 2019;572(7771):595–602. doi:10.1038/s41586-019-1493-8
4. Goh PS, Ismail AF, Ng BC. Directional alignment of carbon nanotubes in polymer matrices: Contemporary approaches and future advances. Compos Part A Appl S. 2014;56:103–126. doi:10.1016/j.compositesa.2013.10.001
5. Salah LS, Ouslimani N, Bousba D, Huynen I, Danlée Y, Aksas H. Carbon nanotubes (CNTs) from synthesis to functionalized (CNTs) using conventional and new chemical approaches. J Nanomater. 2021:1–31. doi:10.1155/2021/4972770
6. Peng HJ, Huang JQ, Zhao MQ, Zhang Q, Cheng XB, Liu XY, Wei F. Nanoarchitectured graphene/CNT@ porous carbon with extraordinary electrical conductivity and interconnected micro/mesopores for lithium-sulfur batteries. Adv Func Mater. 2014;24(19):2772–2781. doi:10.1007/s10853-015-9440-z
7. Ma PC, Siddiqui NA, Marom G, Kim JK. Dispersion and functionalization of carbon nanotubes for polymer-based nanocomposites: A review. Compos Part A Appl S. 2010;41(10):1345–1367. doi:10.1016/j.compositesa.2010.07.003
8. Kausar A, Rafique I, Muhammad B. Review of applications of polymer/carbon nanotubes and epoxy/CNT composites. Polym Plast Technol. 2016;55(11):1167–1191. doi:10.1080/03602559.2016.1163588
9. Venkataraman A, Amadi EV, Chen Y, Papadopoulos C. Carbon nanotube assembly and integration for applications. Nanoscale Res Lett. 2019;14(1):1–47. doi:10.1186/s11671-019-3046-3
10. Chen J, Liu B, Gao X, Xu D. A review of the interfacial characteristics of polymer nanocomposites containing carbon nanotubes. RSC Adv. 2018;8(49):28048–28085. doi:10.1039/C8RA04205E
11. Nurazzi NM, Sabaruddin FA, Harussani MM, Kamarudin SH, Rayung M, Asyraf MRM, Khalina A. Mechanical performance and applications of CNTs reinforced polymer composites – A review. Nanomaterials Basel. 2021;11(9):2186. doi:10.3390/nano11092186
12. Shoukat R, Khan MI. Carbon nanotubes: a review on properties, synthesis methods and applications in micro and nanotechnology. Microsyst Technol. 2021;1–10. doi:10.1007/s00542-021-05211-6
13. Wu X, Mu F, Zhao H. Recent progress in the synthesis of graphene/CNT composites and the energy-related applications. J

Mate Sci Technol. 2020;55:16–34. doi:10.1016/j.jmst.2019.05.063

14. Cho W, Schulz M, Shanov V. Growth and characterization of vertically aligned centimeter long CNT arrays. Carbon. 2014;72:264–273. doi:10.1016/j.carbon.2014.01.074
15. Ding D, Wang J, Yu X, Xiao G, Feng C, Xu W, He G. Dispersing of functionalized CNTs in Si–O–C ceramics and electromagnetic wave absorbing and mechanical properties of CNTs/Si–O–C nanocomposites. Ceram Int. 2020;46(4):5407–5419. doi:10.1016/j.ceramint.2019.10.297
16. Mohd Nurazzi N, Asyraf MM, Khalina A, Abdullah N, Sabaruddin FA, Kamarudin SH, Ahmad S, Mahat AM, Lee CL, Aisyah HA, Norrrahim MNF, Ilyas RA, Harussani MM, Ishak MR, Sapuan SM. Fabrication, functionalization, and application of carbon nanotube-reinforced polymer composite: An overview. Polymers Basel. 2021;13(7):1047. doi:10.3390/polym13071047
17. Ramachandran K, Boopalan V, Bear JC, Subramani R. Multi-walled carbon nanotubes (MWCNTs)-reinforced ceramic nanocomposites for aerospace applications: a review. J Mater Sci. 2022;57(6):3923–3953. doi:10.1007/s10853-021-06760-x
18. Temizel-Sekeryan S, Wu F, Hicks AL. Global scale life cycle environmental impacts of single-and multi-walled carbon nanotube synthesis processes. Int J LCA. 2021;26:656–672. doi:10.1007/s11367-020-01862-1
19. Norizan MN, Moklis MH, Demon SZN, Halim NA, Samsuri A, Mohamad IS, Abdullah N. Carbon nanotubes: Functionalisation and their application in chemical sensors. RSC Adv. 2020;10(71):43704–43732. doi:10.1039/D0RA09438B
20. Ferrier DC, Honeychurch, KC. Carbon nanotube (CNT)-based biosensors. Biosensors. 2021;11(12):486. doi:10.3390/bios11120486
21. Wan H, Cao Y, Lo LW, Zhao J, Sepulveda N, Wang C. Flexible carbon nanotube synaptic transistor for neurological electronic skin applications. ACS Nano. 2020;14(8):10402–10412. doi:10.1039/C9TA12494B
22. Kim JA, Seong DG, Kang TJ, Youn JR. Effects of surface modification on rheological and mechanical properties of CNT/epoxy composites. Carbon. 2006;44(10):1898–1905. doi:10.1016/j.carbon.2006.02.026
23. Dehrooyeh S, Vaseghi M, Sohrabian M, Sameezadeh M. Glass fiber/Carbon nanotube/Epoxy hybrid composites: Achieving superior mechanical properties. Mech Mater. 2021;161:104025. doi:10.1016/j.mechmat.2021.104025
24. Cha J, Jin S, Shim JH, Park CS, Ryu HJ, Hong SH. Functionalization of carbon nanotubes for fabrication of CNT/epoxy nanocomposites. Mater Design. 2016;95:1–8. doi:10.1016/j.matdes.2016.01.07
25. Jakubinek MB, Ashrafi B, Zhang Y, Martinez-Rubi Y, Kingston CT, Johnston A, Simard B. Single-walled carbon nanotube–epoxy composites for structural and conductive aerospace adhesives. Compos B Eng. 2015;69:87–93. doi:10.1016/j.compositesb.2014.09.022
26. Aradhana R, Mohanty S, Nayak SK. A review on epoxy-based electrically conductive adhesives. IJAA. 2020;99:102596. doi:10.1016/j.ijadhadh.2020.102596
27. Banerjee P, Bhattacharjee Y, Bose S. Lightweight epoxy-based composites for EMI shielding applications. J Electron Mater. 2020;49:1702–1720. doi:10.1007/s11664-019-07687-5
28. Butt HA, Lomov SV, Akhatov IS, Abaimov SG. Self-diagnostic carbon nanocomposites manufactured from industrial epoxy masterbatches. Compos Struct. 2021;259:113244. doi:10.1016/j.compstruct.2020.113244
29. Butt HA, Owais M, Sulimov A, Ostrizhiniy D, Lomov SV, Akhatov IS, Popov YA. CNT/Epoxy-Masterbatch Based Nanocomposites: Thermal and Electrical Properties. In: Proceedings of the Conference “IEEE 21st International Conference on Nanotechnology (NANO)”. 2021 July 28–30; Montreal, Canada. p. 417–420.
30. Jafarypouria M, Mahato B, Abaimov SG. Separating Curing and Temperature Effects on the Temperature Coefficient of Resistance for a Single-Walled Carbon Nanotube Nanocomposite. Polymers Basel. 2023;15(2):433. doi:10.3390/polym15020433
31. Salikhov RB, Zilberg RA, Mullagaliev IN, Salikhov TR, Teres YB. Nanocomposite thin film structures based on polyarylenephthalide with SWCNT and graphene oxide fillers. Mendeleev Commun. 2022;32(4):520–522. doi:10.1016/j.mencom.2022.07.029
32. Khuzin AA, Tuktarov AR, Venidiktova OV, Barachevsky VA, Mullagaliev IN, Salikhov TR, SalikhovRB, Khalilov LM, Khuzina LL, Dzhemilev UM. Hybrid molecules based on fullerene C60 and dithienylethenes: synthesis and photochromic properties, optically controlled organic field-effect transistors. Photochem Photobiol. 2022;98(4):815–822. doi:10.1111/php.13539
33. Tuktarov AR, Salikhov RB, Khuzin AA, Safargalin IN, Mullagaliev IN, Venidiktova OV, Valova TM, Barachevsky VA, Dzhemilev UM. Optically controlled field effect transistors based on photochromic spiropyran and fullerene C60 films. Mendeleev Commun. 2019;29(2):160–162. doi:10.1016/j.mencom.2019.03.014
34. Tuktarov AR, Salikhov RB, Khuzin AA, Popod'ko NR, Safargalin IN, Mullagaliev IN, Dzhemilev UM. Photocontrolled organic field effect transistors based on the fullerene C60 and spiropyran hybrid molecule. RSC Adv. 2019;9(13):7505–7508. doi:10.1039/C9RA00939F
35. Salikhov RB, Lachinov AN, Bunakov AA. Charge transfer in thin polymer films of polyarylenephthalides. Phys Solid State. 2007;49(1):185–188. doi:10.1134/S1063783407010295
36. Salikhov RB, Lachinov AN, Rakhmeyev RG. Electrical properties of heterostructure Si poly (diphenylenephthalide) Cu. J Appl Phys. 2007;101(5):053706. doi:10.1063/1.2450679
37. Zang X, Zhou Q, Chang J, Liu Y, Lin L. Graphene and carbon nanotube (CNT) in MEMS/NEMS applications. Microelectron Eng. 2015;132:192–206. doi:10.1016/j.mee.2014.10.023
38. Han W, Fan S, Li Q, Hu Y. Synthesis of gallium nitride nanorods through a carbon nanotube-confined reaction. Sci. 1997;277(5330):1287–1289. doi:10.1126/science.277.5330.1287
39. Sandoval S, Kierkowicz M, Pach E, Ballesteros B, Tobias G. Determination of the length of single-walled carbon nanotubes by scanning electron microscopy. MethodsX. 2018;5:1465–1472. doi:10.1016/j.mex.2018.11.004
40. Huang X, Farra R, Schlögl R, Willinger MG. Growth and termination dynamics of multiwalled carbon nanotubes at near ambient pressure: an in situ transmission electron microscopy study. Nano Lett. 2019:19(8):5380–5387. doi:10.1021/acs.nanolett.9b01888
41. Wu Y, Lin X, Zhang M. Carbon nanotubes for thin film transistor: fabrication, properties, and applications. J Nanomater. 2013:64–64. doi:10.1155/2013/627215
42. Zhao J, Gao Y, Gu W, Wang C, Lin J, Chen Z, Cui Z. Fabrication and electrical properties of all-printed carbon nanotube thin film transistors on flexible substrates. J Mater Chem. 2012;22(38):20747–20753. doi:10.1039/C2JM34598F
43. Salikhov RB, Abdrakhmanov VK, Yumalin TT. Experience of Using Bluetooth Low Energy to Develop a Sensor Data Exchange System Based on the NRF52832 Microcontroller. In: Proceedings of the Conference “2021 International Ural Conference on Electrical Power Engineering (UralCon)”. 2021 Sep 24–26; Magnitogorsk, Russia. p. 229–233.
44. Bandaru PR. Electrical properties and applications of carbon nanotube structures. J Nanosci Nanotechnol. 2007;7(4–5):1239–1267. doi:10.1166/jnn.2007.307
45. Bauhofer W, Kovacs JZ. A review and analysis of electrical percolation in carbon nanotube polymer composites. Compos Sci Technol. 2009;69(10):1486–1498. doi:10.1016/j.compscitech.2008.06.018
46. Salikhov TR, Abdrakhmanov VK, Yumalin TT. Application of Organic Sensors in Wireless Environmental Monitoring Systems. In Proceedings of the Conference “2021 International Conference on Electrotechnical Complexes and Systems (ICOECS)”. 2021 Nov 16–18; Ufa, Russia. p. 500–503.

47. Mustafin AG, Latypova LR, Andriianova AN, Salikhov SM, Usmanova GS, Mullagaliev IN, Salikhov RB. Polymerization of new aniline derivatives: synthesis, characterization and application as sensors. RSC Adv. 2021;11(34):21006–21016. doi:10.1039/D1RA02474D
48. Gardea F, Lagoudas DC. Characterization of electrical and thermal properties of carbon nanotube/epoxy composites. Compos Part B Eng. 2014;56:611–620. doi:10.1016/j.compositesb.2013.08.032
49. Pejcic B. Modifying the response of a polymer-based quartz crystal microbalance hydrocarbon sensor with functionalized carbon nanotubes. Talanta. 2011;85(3):1648–1657. doi:10.1016/j.talanta.2011.06.062
50. Mondal RK. Novel hybrid nanocarbons/poly (dimethylsiloxane) composites based chemiresistors for real time detection of hazardous aromatic hydrocarbons. Carbon. 2016;100:42–51. doi:10.1016/j.carbon.2015.11.055
51. Cooper JS. Performance of graphene, carbon nanotube, and gold nanoparticle chemiresistor sensors for the detection of petroleum hydrocarbons in water. J Nanopart Res. 2014;16:1–13. doi:10.1007/s11051-013-2173-5