



Recent advancements in transparent carbon nanotube films: chemistry and imminent challenges

Samarjeet Singh Siwal^{1,2} · Adesh Kumar Saini³ · Saptak Rarotra⁴ · Qibo Zhang^{1,5} · Vijay Kumar Thakur^{6,7} 

Received: 9 September 2020 / Accepted: 5 December 2020 / Published online: 6 January 2021
© Crown 2021

Abstract

Carbon nanotube (CNT)-doped transparent conductive films (TCFs) is an encouraging option toward generally utilized indium tin oxide-dependent TCFs for prospective stretchable optoelectronic materials. Industrial specifications of TCFs involve not just with high electrical performance and transparency but also amidst environmental resistance and mechanical characteristic; those are usually excused within the research background. Though the optoelectronic properties of these sheets require to be developed to match the necessities of various strategies. While, the electrical stability of single-walled CNT TCFs is essentially circumscribed through the inherent resistivity of single SWCNTs and their coupling confrontation in systems. The main encouraging implementations, CNT-doped TCFs, is a substitute system during approaching electronics to succeed established TCFs, that utilize indium tin oxide. Here we review, a thorough summary of CNT-based TCFs including an overview, properties, history, synthesis protocol covering patterning of the films, properties and implementation. There is the attention given on the optoelectronic features of films and doping effect including applications for sophisticated purposes. Concluding notes are given to recommend a prospective investigation into this field towards real-world applicability.

Graphic abstract

This graphical abstract shows the overview of different properties (mechanical, electrical, sensitivity and transportation), synthesis protocols and designing (dry and wet protocol, designing by surface cohesive inkjet-printed and the support of polymers), doping effect (general doping, metal halides, conductive polymers and graphene for transparent electrodes) and

✉ Qibo Zhang
qibozhang@kust.edu.cn

✉ Vijay Kumar Thakur
vijay.thakur@cranfield.ac.uk

¹ Key Laboratory of Ionic Liquids Metallurgy, Faculty of Metallurgical and Energy Engineering, Kunming University of Science and Technology, Kunming 650093, People's Republic of China

² Department of Chemistry, M.M. Engineering College, Maharishi Markandeshwar (Deemed To Be University), Mullana-Ambala, Haryana 133207, India

³ Department of Biotechnology, Maharishi Markandeshwar (Deemed To Be University), Mullana-Ambala, Haryana 133207, India

⁴ Energy Research Institute At Nanyang Technological University, Research Techno Plaza, 50 Nanyang Drive, Singapore 637553, Singapore

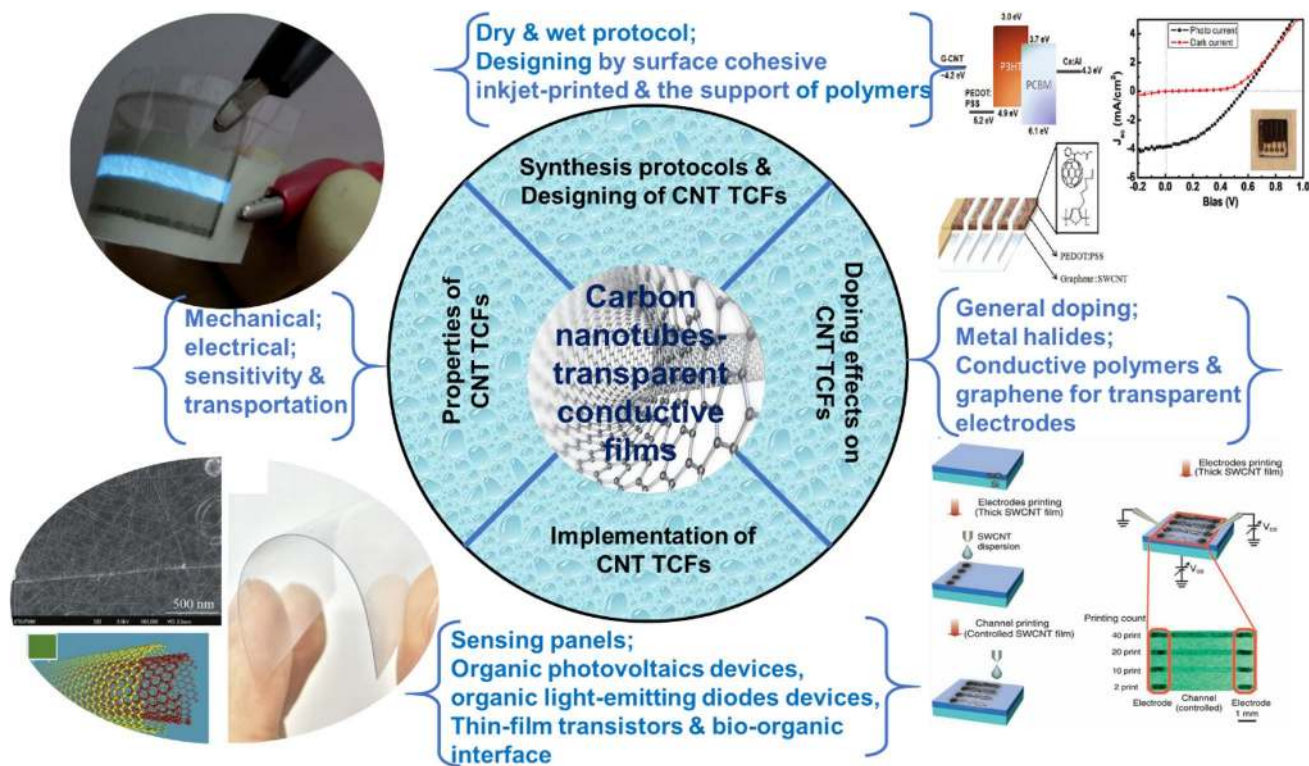
⁵ State Key Laboratory of Complex Nonferrous Metal Resources Cleaning Utilization in Yunnan Province, Kunming 650093, People's Republic of China

⁶ Biorefining and Advanced Materials Research Center, Scotland's Rural College (SRUC), Kings Buildings, Edinburgh EH9 3JG, UK

⁷ Department of Mechanical Engineering, School of Engineering, Shiv Nadar University, Greater Noida, Uttar Pradesh 201314, India



implementations (sensing panels, organic light-emitting diodes devices, thin-film transistors and bio-organic interface) of carbon nanotubes transparent conductive films.



Keywords Transparent conducting films · Carbon nanotubes · Doping effect · Organic photovoltaics devices

Introduction

Transparent conductive films (TCFs) are an essential ingredient of different optoelectronic gadgets, for example, sensing displays, smart gadgets, liquid crystal displays (LCDs), organic light-emitting diodes (OLEDs), and organic photovoltaic (OPV) devices [1–3]. Indium tin oxide (ITO) generally holds the applied translucent conductive substance including an excellent electrical and optical characteristics; though, the bound resources of indium and the fragile quality of ITO control its sustainable purpose into elastic electronics [4, 5]. Recently, ITO is the predominant element employed for large range TCF uses. ITO has unique features besides a sheet resistance of $10 \Omega \text{ sq}^{-1}$ at around 90% visual transmission, shows excellent durability and adaptability through equally wet and dry equipment methods. Though, expected optoelectronics need TCF substances those are mechanically flexible, insubstantial and lower assembly price [6–10]. The increasing market toward ITO owing to the growth of solar cells can drive to an improvement in the price. This increase in the actual value is due to the comparatively intermittent component of indium. Also, ITO bears by weak mechanical

versatility, that contains its employment for developing elastic, stretchable and wearable electronic forms.

Among the developing and accelerated growth of elastic electronic materials, substitute transparent conductive substances beside excellent compliance have been studied, along with carbon nanotubes (CNTs) [11, 12], graphene (Gr) [13], metal nanowires (MNWs) [14], conducting polymers (CPs) [15, 16], and several amalgams [17, 18]. Amongst all, single-wall CNTs (SWCNTs) are an attractive nominee because of its excellent electrical activity, high architectural resistance, enormous versatility, and acceptable optical characteristics, for example, lower refractive index, slight pigmentation, and lower mist [19]. In the previous years, the notable attempt has been devoted for achieving excellent movement towards SWCNT-depend TCFs employing correspondingly wet [11, 20] and dry methods [21]. Though, the electrical behavior of SWCNT TCFs is yet not excellent as ITO and happens very low of what may be required by the electric and photosensitive characteristics of singular SWCNTs [22]. The expectancy toward the subsequent 5–10 years is that the need to CNTs will regularly increase, as long as price/property, clearness and composition yield

problems are overwhelmed. The cost of CNTs has been varying significantly in the prior several years, being reliant on their pureness and prototype along with the supplier. The MWCNTs price is typically within US\$ 0.5–100/g, while DWCNTs may be purchased for about US\$ 10/g. The price of SWCNTs also changes a lot, regularly within US\$ 20–2000/g [23].

Kumanek et al. [24] demonstrated how exposure of the material to a hostile sound wave environment can be limited by the application of another preprocessing step. Initially, SWCNTs, were pulverized in a common style grinder, which empowered the de-collection thereof. This unsophisticated method enables a high-quality CNT dispersion at concentrated sonication time. The electrical conductivity of high-quality CNT dispersion was enhanced by four times as compared with unground material, reaching a high value of 1067 ± 34 S/cm. Marzari and Elise [25] studied conductance preserving model to study the effect of covalent linkers, utilized in nitrene-pyrazine case as cycloadditions, which give the answer to lower electric performance. The electric performance can be increased by characterizing the function of transition-metal adsorbates in refining mechanical coupling and electrical tunneling between the tubes. The electrical conductivities can be enhanced by employing different methodologies such as an accumulative increase the quantity of silver particles and sizes. The trials containing high aspect values AgNWs having a lower value of percolation and attained higher values of electrical conductivity of 1.3 ± 104 S/cm at 9 vol % of Ag content, at room temperature [26].

These important drawbacks of ITO have been urging the quest for substitute TCF elements for automated use with new metal oxides (MoO_x), polymers [27], MNWs, and carbon-based materials [28]. The substitute MoO_x may apply overflowing ingredients, for example, FTO (fluorine-doped tin oxide, SnO_2 : F), aluminium-doped copper oxide (CuO_2 : Al) and AZO (Aluminium-doped zinc oxide, ZnO : Al) [29–31]. Alike towards ITO, TCF incorporation of these oxides needs a vacuity and elevated-heat method for obtaining high transmission and low film protection. The cost of ITO TCFs is overshadowed with the price of bulk construction relatively compared to the price of indium. Suspension treated oxide TCFs have been drawing attention as economic expertise [32].

As the previous years, the application of TCFs has been improved owing to the extensive usage of commodities into our everyday living, for example, mobile phones with sensing boards and LCDs. Recently, the common substance toward TCFs is transparent and conductive doped MoO_x , which is a full-fledged technology but also has few issues, i.e. breakability and expensive incorporation. Though, a significant attempt has been employed at CPs, but not in a situation to substitute TCOs during the incorporation of TCFs owing to their lower

ecological resistance. Owing to their outstanding electrical performance, mechanical adaptability, including optically inactive pigment, CNTs have been largely doped and studied under TCFs and exhibit high possible material for industrial utilization. A wide kind of protocols has been produced to synthesize and design the final CNT TCFs.

Yet another possibility for TCF substances are the metallic nano-compositions, with metal sheets, conductive terminals, and MNWs, which have been conferred to present more beneficial characteristics compare to TCOs at plastic supports [33–38]. Though, the metallic compositions usually show a cloudy vision, which is inconsistent among the image purposes but is useful in different photovoltaics [39]. Metallic nanoparticles (MNPs) are generally formed by silver, that has a comparable price near indium, indicating there is a slight economic advantage while applying MNPs. Moreover, the chemical, thermal and longtime durability of TCFs as of MNPs are unreliable, including several articles conferring quick degeneration of characteristics and leaching [40, 41].

This is an exciting opportunity for materials investigators because of the broader scope towards contemporary substances which are fit to TCFs, but none one of the individuals is recently perfect toward industrial-range, ageing manufacturing fib. As of the determined growth of innovative commodities dependent upon TCFs (for example, yearly upgrading smartphones), the price of substances, production, and price of production will remain to designate a hurdle in this growing industry. Therefore, an investigation obsessed with a modern era of substances towards TCFs is needed. Related to TCOs and another alternative, CNTs have a range of benefits with an excess of carbon substantial, great internal electrical characteristics including high versatility, the comfort of solution-grounded dealing out on ambient condition, chemical durability, and a broad spectral area of transmission including a vague cooler [42]. In this review article initially, we explain the history and overview of CNTs-based TCFs, follow with an advantage and a necessity of TCFs. Subsequently, we addressed the properties of CNT TCFs, including; mechanical, electrical, sensitivity and transportation towards practical aspects. Next to this, we explained the synthesis and incorporation protocols of the CNT TCFs including a targeting summery towards CNT composite sheets, intrinsic optoelectronic characteristics and then concluding by a review of inherent different implementations concentrating on OPVs, sensing panels, OLEDs, thin-film transistor and bio-organic interface. In the last, we concluded our article with future outlooks in this field.



History and overview of CNT TCFs

History of CNTs

CNTs are carbon-based nanomaterials including deep hollow arrangement and width in the nanometer range. CNTs defines in SWCNTs and multiwalled CNTs (MWCNTs), are the absolute one-dimensional substance including the width in nanometer scale, maintaining the leading electrical, thermic, mechanical, and optical characteristics [43–46]. Historically, MWCNTs were initially identified during 1991 [47], and afterwards, SWCNTs were originated in the year 1993 [48]. Based on the concentric cylinders, MWCNTs can be recognized as the incorporation of several film SWCNTs. Indeed, CNTs are driven with the hexagonal pattern graphene on the particular and discrete angles. The several chirality's and the widths of CNTs would drive forward towards the diverse optical characteristics. An SWCNT is comparable as a turn-up, individual 2D graphene film during controlling the carbon molecules within the sp^2 hybridized system [49]. Consequently, owing to the bend tempted misorientation of p orbitals into the carbon system, the variation of the electric field by the zero-bandgap half-metallic of graphene towards a blend of conducting and semi-metal, liable on the systematic point [50].

Furthermore, Wang et al. [51] proposed a consecutive synthesis, deposition, and transference procedure toward the incorporation of high-performance SWCNT thin sheets of meter-scale dimension including significant optoelectrical activity. Figure 1a, b displays a schematic and image of the device employed toward the growth, accumulation, and transference of SWCNTs to incorporate large-area SWCNT transparent sheets. Figure 1c, d exhibits images of two large-area SWCNT layers shifted upon a resilient poly(ethylene terephthalate) (PET) support. A fluid dynamics simulation of the gas velocity dispersion into the gas-filtration operation was taken out. Figure 1e manifests the simulation outcome of the linear dependency of the exit gas velocity (V_{out}) upon the gas velocity on the free edges of the separation operation (V_{free}). Figure 1f confers a consistent velocity pattern into the gas stream within the percolation mode near the equilibrium phase, showing that a constant SWCNT deposition method is probable.

As TCF uses, the most significant transport characteristics have been well-investigated. Amongst these characteristics, the electrical performance is the utmost significance in respect of presenting a solid basis to incorporate transparent tinny layers including high activity. Furthermore, the superior mechanical and thermal characteristics expressively expand its use within the manufacturing of TCFs. Although, largest of these characteristics of a CNT

is extremely anisotropic and with its rotational path, that acts few hurdles toward actual manufacturing utilization [52].

Overview of TCFs

Owing to the fast growth of electronic devices, the requirement toward TCFs has grown more essential. Further rigorous demands on the physical and chemical characteristics of conducting substances have to be placed ahead. To this aim, many investigations concerning flexible TCFs have been brought combining distinct conductive nanomaterials, for example, carbon nanomaterials [13], metallic nanowires [53], nanoparticles [54], and conductive polymers [55].

Therefore, TCFs have discovered utilization under a broad category of optoelectronic and photovoltaic appliances such as flat board displays, touch screens of mobiles and computers, solar cells, OLEDs, antistatic and electromagnetic interfering protecting elements along with heating components for defrosting window ornaments of aircraft and transportations. The possibilities toward TCF employment seems encouraging owing to the increase in screens, touch ornaments and photovoltaics requirements. Up to now, vacuum stumbled transparent conductive oxides (TCOs), for example, ITO, FTO and AZO transparent coatings are used mainly as the transparent probes for these tools. Inappropriate, ITO including high transparency and lower sheet resistance is favored to compare with different TCOs [29, 56, 57]. In current decades, active growth in nanotechnology reveals novel possibilities toward manufacturing nanomaterials, including better chemical, mechanical and physical characteristics. Carbonaceous nanomaterials, for example, graphene and CNTs beside remarkably high elastic modulus of ~1 TPa, excellent mechanical elasticity, high visible transmittance and electrical activity are being acknowledged as best applicants toward transparent conductive electrodes (TCEs) [42, 58].

Generic impact of TCFs

An absolute TCF would represent a low transmittance over the UV–vis–NIR profile and film stability. Essentially this has been done through gauging UV–vis optical density of the TCF to achieve the transmission, during R_s is contained including a four-point or a two-point conductivity exploration. There is an interchange among these two constraints. Hence, to quickly analyze TCFs, the dual main characteristics require to designate linked. Some changes have been introduced, but the furthestmost obvious is the proportion of electric (σ_{dc}) and optical electron transfer (σ_{Op}) [8]. De and his co-workers [59] suggested comparing the complete characteristics of CNT TCFs by several organizations. Although, the σ_{dc}/σ_{Op} proportion is additional widespread and is useful

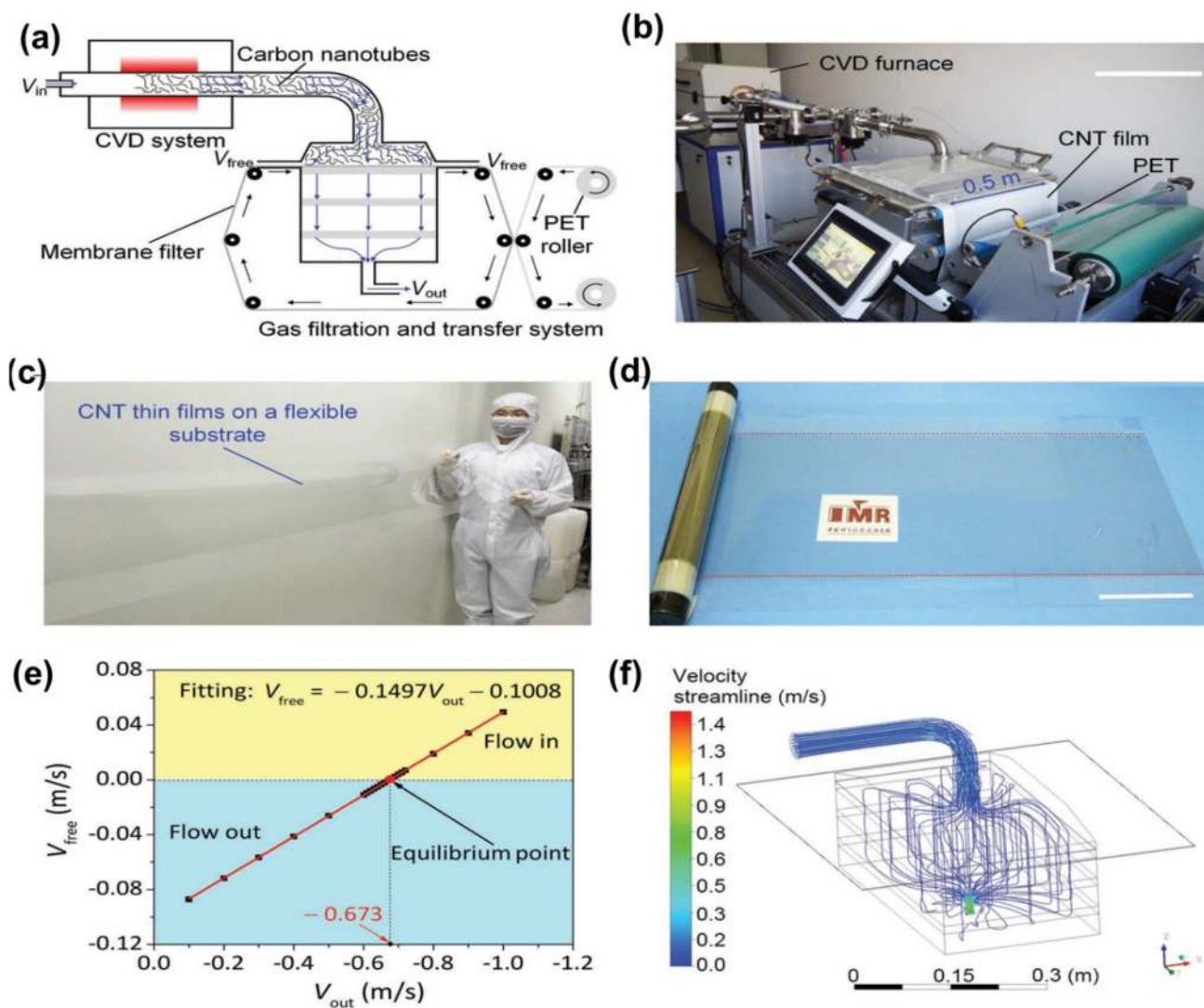


Fig. 1 Formation of meter-range SWCNT thin sheets. **a** Schematic displaying the equipment composed toward the construction, accumulation, and transference of SWCNT layers. **b** A photo of the self-constructed device (range bar, 0.5 m). **c** A SWCNT thin-film carried at pliable PET support including a range of higher than 2 m. **d** A roll of homogenous SWCNT thin sheet at the PET support. **e** Definite-element simulation of the dependency of V_{out} at V_{free} to an inlet gas

velocity $V_{in}=0.068 \text{ m s}^{-1}$. While the top yellow zone, the air from the environment continues in the separation operation ($V_{free} > 0$); in the below cyan zone, the gas in the filtration operation moves out ($V_{free} < 0$); on the equilibrium spot of $V_{out} = -0.673 \text{ m s}^{-1}$, no gas runs inside or out ($V_{free} = 0$). **f** Simulation data revealing a steady velocity spread in the gas stream into the separation practice on the equilibrium position [51]

in analyzing the characteristics of TCFs. Greater rate of σ_{dc}/σ_{op} symbolizes a more conventional TCF display. Therefore, in the subsequent segments, we practice the proportion to relate TCFs features from several works of literature.

A crucial ingredient of current optoelectronic tools is TCFs. So TCFs are applied within the type of new optoelectronic devices, for example, touch screens, LCDs, solar cells and light-emitting diodes (LEDs). ITO is a standard and commonly utilized substance toward TCFs concerning everyday purposes and fulfils enormous requirements for businesses. ITO has outstanding transparency, high conductivity, including the highest figure of benefit. Notwithstanding

having exceptional features, ITO is yet suffering from some significant problems, for example, (i) expensive because of insufficient accessibility of indium origin under the earth and (ii) high fragility of the ITO sheet, which decreases the potential application toward flexible automatics. Consequently, vast research is conducted throughout the scientific community for obtaining a suitable substitute for ITO, and such elements primarily needed to fulfil the market's demand for the modern contemporaries optoelectronic tools [60]. In this respect, researchers are investigating several materials, metals, composites etc. as the potential candidate which can prove worthy in optoelectronic research.

Many new and emerging elements, materials, metals, composites, have been studied as potential candidate. Some examples are like: conductive polymers (CPs), metal plates, CNTs, graphene, and arbitrary arrangements of metal nanowires (Ag/Cu NWs) have been investigated as the new contemporaries TCF supplies to substitute ITO [8, 61–64]. TCFs based upon the solution treated developing lucid conductors confer the advantages such as economic, the efficiency of scalable incorporation, and adaptable characteristics. Standard solution methods during the construction of these new TCF elements, for example, spin-coating, drop-casting, spraying, and dip-coating procedures [65]. TCFs includes a more conventional optical/electrical characteristics, when comparable to ITO sheet may be formed by applying these solution-state coating methods. Although these solution-state techniques are generally employed to laboratory presentations and are difficult to be controlled. Extensive range fabrication method with industrialized potential is significantly required.

Moreover, most optoelectronic characteristics are required for sensing applications. In a sensing board, a TCF must be light, and soft to distort the impact including high transmittance (around 85%). As the practical constraints of a sensing display are essentially inductive, the R_s may be comparatively large $\sim 500 \Omega/\text{square}$. Connecting these constraints provides an expected σ_{dc}/σ_{OP} of around 4.5 Ω/square . Contrarily, the preferably transparent sheets practiced in photovoltaics required to have a high transmission and low R_s to meet the requirement of better holding translucence capacity and having a good conductivity for effective energy accumulation (around 25% competence) [17, 66–68].

The pivotal problem of CNT stability

The steadiness of the electrical behavior of SWCNT material sheets on high temperatures, exceeding 100 °C, is an essential characteristic of SWCNT films at stretchable supports toward electrode uses because electrodes can be disclosed to high heats while the construction method. Consequently, the thermal augmentation of the support has to be agreeable by the SWCNT arrangement film. Distortion of SWCNT channels happens following heating and chilling methods if the coefficients of thermal expansion (CTE) toward the SWCNT material film and the stretchable support are not balanced. This mismatch among the CTE of the model and CNT interface in CNT/polymer catalyst affected thermal remaining radial strain and degradation with the nanotubes while its melt chilled the polymer [69]. Degradation of the SWCNTs which associated by the support changed the inherent electrical performance of the SWCNT system or the terminal resistance of the interface layer. [70, 71]. Han et al. [72] described various constituents which are solutions to the incorporation of very conductive thermally durable SWCNT

coatings at amenable supports. Prominently, this investigation proposes that establishing the interfacial stress among the SWCNT system layers and the top layer substance allows tuning of the electrical conductivity of SWCNT sheets.

The significant benefit of CNT TCFs above ITO lies in their elasticity and mechanical along with chemical robustness linked, including lower heat void-free covering techniques which are fitted among plastic supports. Thin CNT layers have the opportunity to begin industrialization uses such as bendable screens, touch-sensible tools and even stretchable microelectronics will consequently be the usual possible areas. Amongst elastic applications, CNT TCFs will have to carry important price decrease to achieve some of ITO's business part. However, wet accumulation methods might guide to profits in finance and deposition expenses, it may up to now not be calculated if the total covering prices per area will be cheaper compare to ITO or even competing [73].

Concerning any nanocomposite, the atmospheric strength and protection hazard is a function of both risk (i.e., the toxicity of the substance) and disclosure (i.e., the direction or continuation of association by people of concern) [74]. In the last of its user existence, one potential way of discarding to CNT-based commodities includes incineration, subsequent that CNTs can be delivered in the background as incinerator ash [75, 76]. The thermal resistance of CNTs as a role of surface oxidation is essential to acknowledge, as incineration allows the probability of conversion before atmosphere discharge. One more significant correlation to estimate is the outcome of surface oxygen at the sensitivity of CNTs over microbial biodegradation, as fluctuations during the rate of degeneration will manage the chance of susceptibility to different bodies. The cytotoxicity of CNTs united among the disobedience of their aromatic composition induces their regression through microorganisms to be usually delayed or missing, while surface oxidation or disclosure to combined culture bacteria has been determined to improve enzymatic degeneration of CNTs [77].

Properties of CNT TCFs

CNT transparent coatings hold a newer 2D arrangement including a blend of semi-metallic and metallic tunnels. The mechanical, transport and electronic characteristics of single CNTs have been widely investigated and thoroughly recognized. CNT transparent layers will become the typical performance of the particular tunnels by other characteristics originating by the tube-tube synergies. This part will be dedicated toward the characteristics of CNT transparent sheets, including the electric characteristics, for example, work function (WF) and the connection stability beside metals, the transportation characteristics also various geometries

and energy systems, sensitivity properties. The comprehensive appraisal here will lead to the importance of CNT transparent films tools in different applications.

Mechanical properties

The advancements within stretchable electronics have brought broader research attention, and much growth has been invented. Toward bendable electronics, the elasticity of SWCNT TCFs is an essential metric. SWCNTs are essentially stretchable and flexible since of their long facet proportion and adequate atomic connection [78–80]. While supple SWCNTs were grouped within a transparent sheet upon stretchable polymer support, the low-rubbing powers among tubes and bunches [81], the high % void size and the tremendous molecular link within polymer particles and SWCNTs provide the excellent film elasticity, stretch capability, and yet stretchable [82].

Over most extensive and capable applicability, transparent conductors (TC) winding activity is noteworthy. Few distinct parameters, for example, tensile strength and durability, describing stretch capability and wear stability may also be recognized but are each and application-precise or light claiming to develop the mechanical characteristics of TC into turning. Significant attempts have been spent during

the past in the study of multilayer TC sheets, where the neutral axis of bending positions the common crucial fragile (oxide) substance. Though, every fragile substance can't place into the middle of the sheet. Further significantly, the flexural distortions into advanced tools are usually multiaxial occurring in intricate strain ordering designs, that offers this method frequently much more challenging to execute [83].

Shim et al. [84] verified the mechanical characteristics of SWCNT layer-by-layer (LBL) sheet after ITO coverings. The ϵ_c of [PVA/C Sol SWNT + PSS (1 M)]₁₀ LBL film surfaced upon a 230 μm polystyrene (PS) support was 99 and 120% ere and subsequent strong acid processing, sequentially (Fig. 2a). This content shows *ca.* 100 times of developments in their twisting activity than that of the corresponding ITOs. The resistance variations during low strain scale equal to 5 mm turning range of equally extending and squeezing are exhibited inside Fig. 2b–d. Figure 2e displays the bending picture of the SWCNT LBL layer at the PS support. The reported LBL TC sheets may be quickly dropped at a large-scale report paper dimension plastic support into the lab (Fig. 2f).

The correlation in ITO and SWCNT layers is considerably unveiling. Notwithstanding the evidence of complete and more reliable enforcement, the combined value is not as high as one might assume depended upon mechanical

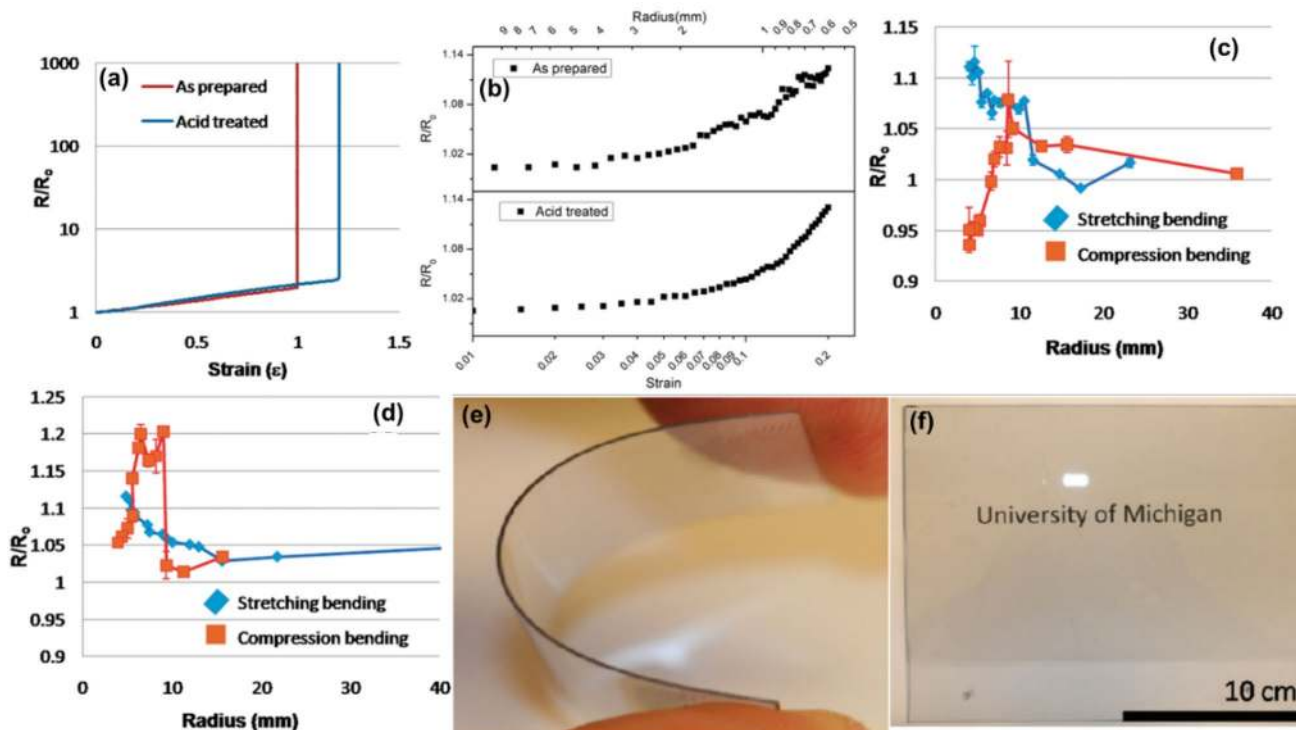


Fig. 2 a–d Electrical resistance variations of [PVA/C Sol SWCNT + PSS (1 M)]₁₀ LBL sheets covered at a supple 230 m dense PS support. Photograph of **e** twisting of the SWCNT LBL covering at

the PS support and **f** large-range varnish of an SWCNT LBL TC sheet. Reprinted with permission from Ref. [84]



property, that can be recognized as the evidence to additional advance both optical and electrical properties.

Electrical properties

The band construction of singular CNTs has been broadly investigated [85–87]. The electronic fabrication of equally metallic and semi-metallic CNTs delicately hinges upon the coverage aspect of the Gr film. As semi-metallic CNTs, the bandgap changes by diameter as $E_g \approx 1/R \sim 0.6 \text{ eV/d}$ (nm). To metallic CNTs, a subsequent band gap endures and changes by diameter being $\sim 1/R^2$ [88]. As of O_2 -doping into the air, semi-metallic CNTs present p-type conduct. During design combination, one important problem is the junction shield within CNTs and metal probes. Various substances have different work functions (WF), Fermi levels, and moistening performance by CNTs, and consequently may have distinct junction resistance. It has been validated under investigation, which concentrates on communications working single semiconducting CNTs as an effective way [89].

One more essential feature toward the interface among CNTs and metallic connections is Fermi level restraining. It had been noticed that a CNT is an edge communicated through metal, the compartment is entirely distinct as contrasted toward the metal–semiconductor boundary [90]. The edge within CNTs and metal also hinge on perceptively at heat, electrical field, and the vanishing aspects, including distinct wetting behavior. Researches confirm that the connection confrontation among CNT transparent films and metal is not a problem [91]. The lower connection resistance among CNT sheets and metal is because of the significant number of CNTs on the edge in correspondence, that drives to minimum connection confrontation.

During trials, the aggregated work function of CNT transparent layers, the theoretical computation may catch in a unique CNT chirality, dimensions, tube-tube range, synergy, and the bunch volume. The theoretical estimate may give perspicacity toward more development or alteration of WF to the fancied practice. Chan et al. [92] draw in the description the tube length, division, and tube model during WF estimation. WF alteration is essential for equipment utilization. During field emission tools, declining WF will further reduce the field emission inception potential. To anode utilization under solar cell and OLED tools, more significant WF's will promote charge division. There is an additional feature of the electronic characteristics of CNT transparent sheets, including the Hall effect. Hall effect validates that CNT transparent sheets are a p-type substance, in opposition to maximum probes, those are n-type.

Supercell geometries are adopted for determining the WF. To a big sufficient unit cell, the Fermi energy may be defined as corresponding over the void level, and which enables for obtaining the WF. During the state of SWCNTs

of a measurable distance by different tube-tube blocks the midpoint to midpoint length i.e. D_x , the nanotube is placed in a supercell, as displayed inside Fig. 3a–d. $L + D_v$ provides the lattice constant of the supercell with the z axis; while L and D_v is the tube's length and void stiffness with the tube axis, respectively that is fixed designate 20 \AA during all computations. Figure 3e–h gives the estimated WF's being a function L to covered and H eliminated (3,3) and (5,0) tube orders. The WF hangs on the L and moves in the direction they are fastened mutually, indicating that if the L and density of tubes may constrain into the completion of a pattern, a scheme including very tunable electronic characteristics [92]. Figure 3i confers the computed WF's of interpolated tube packages as functions of the metal combination to different alkali alloys. Overall, the WF vividly reduces by a small number of intercalations. For illustration, the WF of the semi-metallic tube being the HOMO energy. The estimated WF's of the semi-metallic tube is significantly more compared to the metallic ones (Fig. 3j). This reduces continuously with $1/D$ and methods an extrapolation boundary 4.73 eV on $D \rightarrow \infty$ [93].

Sensitivity characteristics

The sensitivity of the electrical performance of SWCNTs on circumstances sprawls under couple peculiarities: (i) group of carbon atoms into an SWCNT are covering particles, which results in current transmitters being straight revealed toward the atmosphere. The variation into electrical conductivity generated through exterior adsorbates by the neighboring atmosphere is critical as compared to a substance including current conveyors within; (ii) carbon particles have a modest electron connection and a considerable number of adsorbates which have been identified including the strength of charge transmission toward or by them. These outcomes during the change of the Fermi level of SWCNTs, that is also named adsorption-induced chemical incorporating and has been thoroughly studied under graphite intercalation composites and CPs [94].

One main benefit of CNT-based TCFs is their unimaginative and low visual consumption while associated with other general TCFs. In-depth, the Vis–NIR transmission profile of various conductive substances [95], with CNT, ITO, poly(3,4-ethylene dioxathiophene)-poly-(styrene sulfonate) (PEDOT: PSS), graphene, and Ag electrodes. In respect of Ag networks, the appearance improves with growing wavelength. As a conclusion, the transmission of the metallic electrode (Ag) starts to decline near the NIR range [96].

Transportation properties

The transport characteristic of CNTs will lie at the tube dimension, along with the bundling. Because of its wide

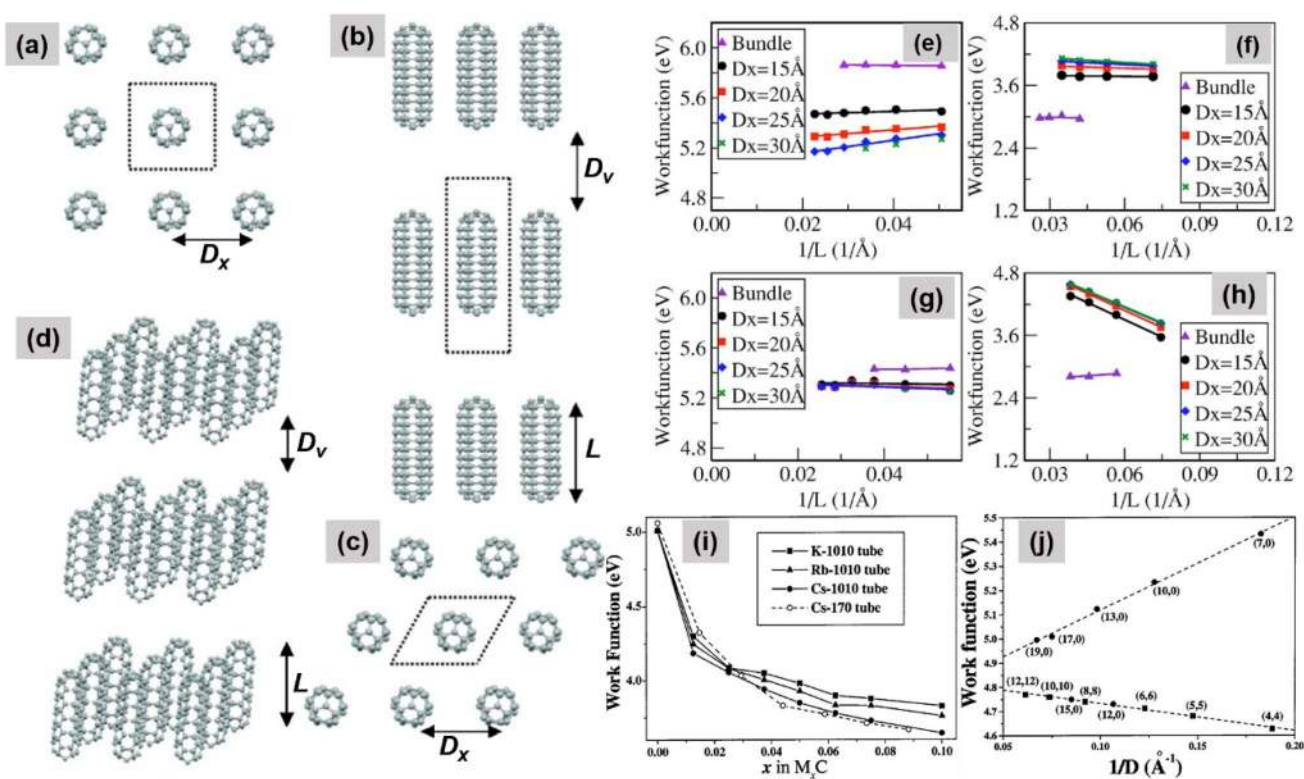


Fig. 3 The schematic figure explains the organization of the nanotubes within the pattern. Dashboards **a** and **b** are the tops and front illustrations to tubes designed in a feigned square pattern, and panels **c** and **d** present the hexagonal form of tubes into a tube bunch. WF's of **e** covered (3,3), **f** H-eliminated (3,3), **g** covered (5,0), and **h** H-eliminated (5,0) SWCNTs of several tube-tube length D_x vs $1/L$.

aspect proportion, CNT channels will have shallow filtration inception. In contrast, the layer thickness raises this figure out some ways for moving the current that will raise higher than straightly by the tube sheets owing to the coupling among several films. Such an edge by 2D to 3D will drive toward a width dependency of the DC activity toward CNT layers. A comparable appearance happens while narrowing the sheet diameter since it fits near to the expansion of CNTs. Herewith, the conducting way move toward the tubes on end will be prevented, and the conductivity will exhibit a dependency at the film diameter. In the next part, we will address the consequence of calculation at the transport characteristic initial, later through the impact of transparency and synthesis approaches.

Charge-transportation and transparency of CNT TCFs

Categorization in CNT-polymer alloy arrangements has been extensively investigated, at which CNTs gives the conduction route into practice. The method gives a 3D filtration compartment and the electrical performance which alters various degrees of magnitude above a low scale of CNT

The perpendicular lines are the straight acceptable of similar facts. Reprinted with permission from Ref. [92]. WF's (eV) of (i) alkali-metal inserted CNT bunches vs the intercalation density (x in $M xC$, M symbolizes metal) and (j) specific metallic and semi-metallic SWNTs vs $1/D$ (squares and dots show armchair and zigzag SWNT's, respectively). Reprinted with permission from Ref. [93]

storing. Toward a transparent layer of CNTs at flat support, the obstacle displays a 2D separation mode [97]. Usually, a CNT system contains mutually metallic and semi-metallic SWCNTs including various units and chirality. The densities of CNT sheets including transmission greater as compared to 70% are normally from sub-nanometer to 50 nm. In an obvious pattern, the charge vectors can be conceived of as conveying with an individual CNT and later bouncing to different CNT at the coupling, but it is important to further complex than that in actuality. The extensively utilized separation method is used to investigate transportation performance towards transparent CNT-based systems [98–100].

The charge-transportation characteristics of CNT TCFs are reliant on several other constituents, with the incorporating amount and transparency, of the CNTs. With all, the cleanliness of the CNTs performs a significant position in defining the resistance of the sheets as any spongy carbon substance and sp^3 hybridized within the system are architectural defects driving towards charge distributing and stability. It is obvious as sheets presenting a low D/G band proportion (a pattern of architectural breaks) during the Raman spectrum (RS) have more reliable conductance

[101]. Particularly, the development of R-COCl combinations with the CNT with SOCl_2 has the incorporating impact which may enhance the optoelectronic characteristics of the CNT sheets vividly [102].

In brief by theoretical and investigational outcomes, CNT dimension, broadness, and preparation process; the metallic and semi-metallic SWCNT proportion; and the arrangement and the pureness of the CNTs each perform a part during the electrical performance of the CNT TCFs [103, 104]. While used to practical conditions, a tradeoff lives among transportation characteristics of the TCF and purity and price of construction. The subsequent segment will examine and analyze basic CNT TCF development techniques.

Synthesis of CNT-based TCFs

Initially, CNT-based TCFs was invented by Wu [20], Saran [105] and their coworkers by applying percolation-transmission and dip-coating techniques, sequentially. CNT-based TCFs have been recognized as the utmost encouraging applicant to substitute ITO. CNT-based TCFs may be manufactured through dry or wet methods, at which the main distinction suspension is employed or not.

Dry protocols

CNTs may be provided through different protocols such as chemical vapor deposition (CVD), laser abscission, and arc-liberation. Usually, towards dry methods, CVD is incorporated to quickly develop the CNT layer, or carry the CNT aerosol to layer [106–109]. As a consequence, dry protocols CNT films show higher class besides the sufficient distinct singular CNTs, some spots, and more significant CNT-CNT touch, related including solution methods. This has been published that dry protocols CNT-TCF conferred a film resistance about $84 \Omega \text{ sq}^{-1}$ and about 90% transmission [110]. Furthermore, an advanced CVD technology may assemble a carbon nanobud (CNB) sheet, that showed $150 \Omega \text{ sq}^{-1}$ around 97% transmission. During 2010, Feng et al. [17] described a facile roll-to-roll method to create soft and bendable MWCNT TCFs. They then formed a design method, which transformed the perpendicular arrangement of CNTs under 200 mm silicon slice into the parallel arrangement, quickly building a self-supporting, ultrathin, low weight, translucent, and metallic CNT sheet. A roll-to-roll method was employed to incorporate the CNT/polymer film compound layer.

Kauppinen and his coworkers [110] described the disadvantages that may be evaded by employing a dry method to synthesize an SWCNT TCF through sterile gas percolation. Initially, SWCNTs are prepared through a floating catalyst chemical vapor deposition (FCCVD) approach [111].

Certain floating deposited on SWCNTs are provided with the gas stream toward a permeable filter layer on the exit of CVD kiln at which it can be accumulated in a sheet. The width of the sheet is defined with the acquisition period. This can be carried toward different supports through compressing the filter film on it. This technique includes no fluid and the essential characteristics of the SWCNTs are adequately protected. In a concluding note, a dry method has evident benefits compare to wet methods into manufacturing high-active SWCNT TCFs.

Moreover, doping including vacuum-desiccated metal sheets considerably reduced the resistance. In reported literature, CNT-based TCFs displayed sheet resistances around 208 and $24 \Omega \text{ sq}^{-1}$ about 90 and 83.4% transmission, sequentially. The application of specific super-arranged CNT patterns restricts its broad use, though this method is an encouraging way to CNT-based TCFs quickly, efficiently and economically.

Wet protocols

Wet treated CNT-based TCFs are ambitious towards large scale application. This process allows a low heat method, in which void is not required. So, reproduction prices may be considerably reduced. Furthermore, it increases the support choice for different solvents. Synthetic or other nontraditional supports may be utilized. The standard methods for wet methods: (i) formation of CNT distribution; (ii) layer incorporation; and (iii) post-processing with the replacement or incorporating of wetting agent. The characteristics of CNT-based TCFs rely upon the nature of substances, distribution, the surface of CNT film, scatter, and incorporating processing. Feedstock CNTs are within the body of a blackish residue. Owing to their high facet proportion, high superficial area and stimulating van der Waals synergy, CNTs greatly fasten mutually to create bulky packages. There have been several investigation articles and discussions about the formation of CNT distribution [112–118].

Raw SWCNTs are normally initially scattered through ultrasonication within a suspension by the aid of surfactants. That is accompanied through centrifugation that moves an uppermost film of single-scattered SWCNTs in absence of catalysts including large bunches that are tapped to be applied to assemble the sheets. Recently, several wet techniques such as vacuum separating [20], spin covering [119], Langmuir–Blodgett glaze [120], dip layer [105], and spray covering [121] have been grown toward the invention concerning SWCNT TCFs. A clear disadvantage of the wet method is the scattering of SWCNTs including chemical processing normally introduces breaks into the cells. This is also hard to fully exclude the surfactants from the exterior of the SWCNTs, and those deteriorate the optoelectronic activity of the obtaining sheets. Consequently, several



constituents besides the SWCNTs origin, cover, aeration constraints, and the capability of replacement of the surfactants affect the appearance of sheets developed through a wet approach.

Though, it continues a hurdle to scatter ultra-long CNTs (over 10 μm) deprived of breakage or lessening. The three main approaches may be reviewed to scatter CNTs in fluid solutions: (i) straight dispersal of natural CNTs in organic dissolvent; (ii) dispersal of covalently attached CNTs; (iii) dispersal of natural CNTs including support materials, for example, wetting agents or polymers. However, application of dispersants improves the technique levels, and remaining residues enhance the junction resistance among CNTs, dispersant-aid CNT suspension is the extensively utilized process owing to the essential benefits for manufacturing performance. Here, we primarily review dispersant-aid CNT liquid paint towards TCF utilization.

Polymers may be applied to compose scattering with covering CNTs. With adopting proper polymers, for example, cellulose byproducts, surface tension along with the thickness of the distribution may be extensively altered toward different deposition methods by spin coating towards screen print. Though, polymer-aided distribution is not extensively described toward TCF applicability because it is hard to separate the non-conductive polymer which subsequently includes its layer incorporation. Elevated heart hardening

or stable solution method are normally required to eliminate the polymer. Accordingly, it cannot be suitable concerning plastic support or towards mass reproduction.

Designing of CNT thin films

CNTs are ideal carbon allotrope that displays several favorable peculiarities such as high chemical resistance, broad transmission spectrum scale, low price, and particularly high mechanical affability encouraging them as stretchable conductive substances to substitute ITO. Various difficulties should be observed while utilizing Gr and CNTs being the functional ingredient of conductive paints. One is the deep scattering of Gr and CNTs into a type of solvents, and therefore printable paints including high mass density corresponding to aggregate and a presumption would be formed. Owing to the unique chemical durability of CNTs, inherited TCF processing methods deepened at eroding compounds are unusually productive, and few innovative approaches are needed to complete floral CNT TCFs [122, 123].

Though, the conductive cords are obscure and consequently utilized as the substitute for ITO. Considering these benefits of the coffee-loop consequence, conduct CNT designs were developed with inkjet print of the aqueous distribution of CNTs at soft PET support (Fig. 4a–c).

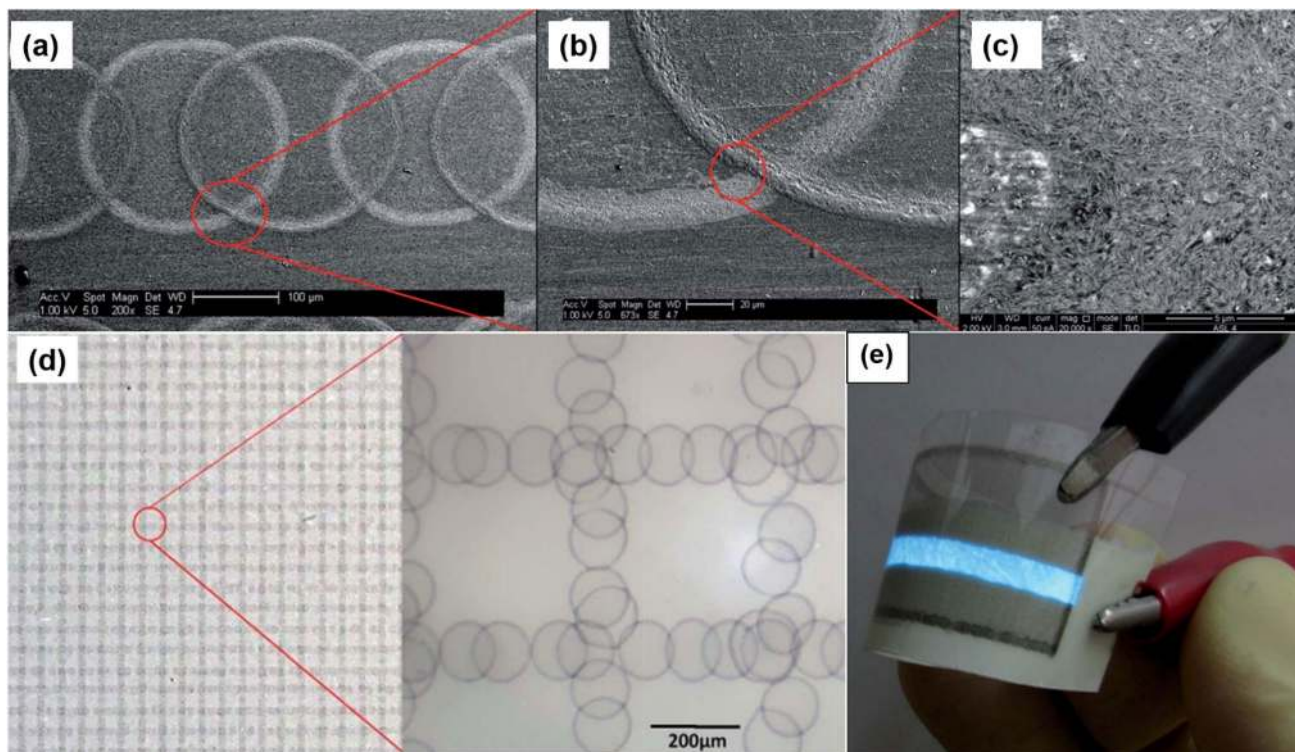


Fig. 4 a–c High-resolution (HR)-SEM and further (FHR)-SEM) pictures of linked rings. **d** The spotted network completed of CNT rings. **e** Super EL tool designed by a thin electrode finished of inkjet-printed CNT rings. Reprinted with permission from Ref. [124]

The high clarity about 81% on 600 nm was obtained with printing specific ring one at the head of the additional, that allowed many films without significantly lowering the clarity [124]. Though particular pristine CNT layers had high stability, and therefore nitric acid post-printing approach was executed to achieve great conductivity ($156 \Omega \text{ sq}^{-1}$). A significant benefit of the recommended approach is that it allows direct incorporation of designed electrodes, as displayed within Fig. 4d. This straight presswork approach is controllable, low price, and could be employed within significant electronic purposes, for example, touch display of mobiles which need designing that is standardly produced with an invaluable and long process such as lithography. Here, this idea described with providing a flexible electro-luminescent (EL) design utilizing the 2D ring order. The tool was made through printing 8 coats of CNT rings. The EL glue was screen-printed, and a complete array of the CNT distribution was inkjet printer (no rings) at the head of the EL adhesive, as the counter probe. As shown in Fig. 4e, the bending concerning the EL can an angle of 180, not influences the electrical activity of the terminals neither the luminance transmitted through the pattern.

Designing has also been shown to be an adequate approach for developing the optoelectronic activity of SWCNT TCFs. Jiang and his coworkers [125] exhibited a micro-structured SWCNT system by placing a micromodel panel filter in a FCCVD operation (Fig. 5a–c). The microprobe reduced the R_s of the TCF though maintaining a large aperture ratio (T). Figure 5d displays the appearance of this unique SWCNT TCF post- HNO_3 incorporating. This may be observed that R_s concerning the SWCNT TCF in the absence of the microprobe about 80% T to 550-nm radiation reduces

by 95 to 53 /sq. with the addition of the microprobe by an A value of about $37.5 \mu\text{m}$. Here, the performance showed the decisive impact of designing SWCNTs upon the TCF activity.

Surface cohesive Inkjet-printed SWCNT-TCFs

Inkjet printing into electronic generation has drawn significant consideration towards the broad scope of uses because it is an eco-friendly and economical method [126–128]. Besides the significant charge-transport characteristics, substances toward inkjet printing must reach another essential necessary, for example, high chemical resistance, low-temperature progression capability, low hysteresis, and low-voltage transaction. Earlier, materials meeting these standards have not been so possible. Here, we discuss economical green construction through specifically established inkjet printing of SWCNT layers.

Initially, designing of the films may be accomplished through inkjet print, that utilizes a CNT paint which needs good wetting characteristics to the support to keep CNTs by specific region command [129, 130]. Though, the resolution is mainly restricted with the support, the solution, and the dimension of the outlet. The main significant point is the synergy among the fluid and the support, that defines the homogeneity of the obtaining film. The plasma processing and fluid with a below sweltering point both define the evaporate, are useful to the formation of a homogenous film [131].

Takenobu et al. [130] developed very thin SWCNT dispersals (Fig. 6a) and constrained mutually the densities and electrical characteristics of the systems with adjusting

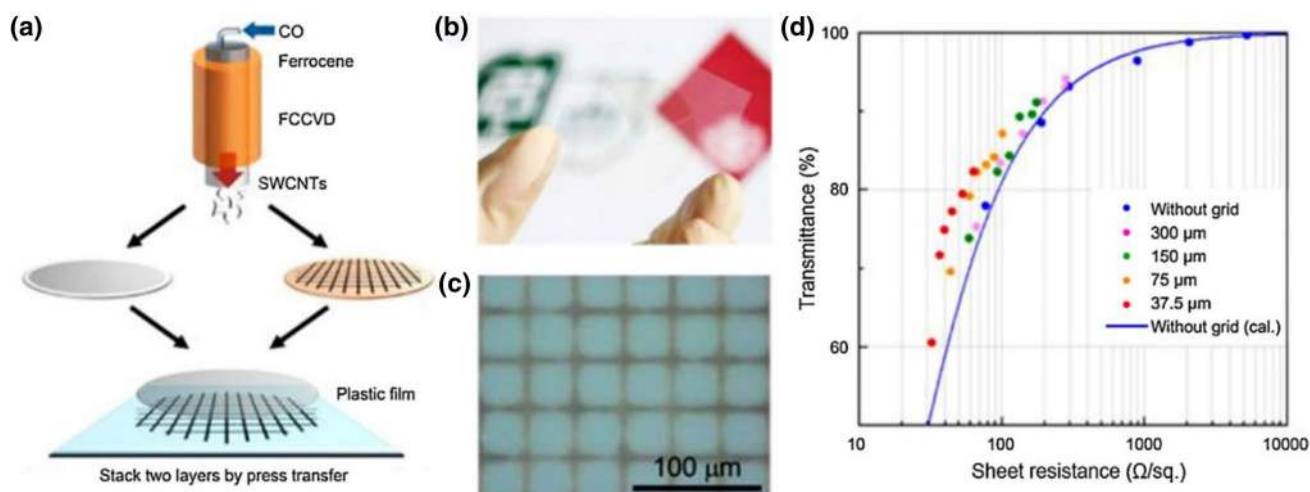


Fig. 5 Invention and analysis of SWCNT TCFs. **a** Representation of the SWCNT TCF manufacturing method including a micro-network. **b** Image of an SWCNT TCF including a micro-network. **c** Optical image concerning the TCF beside a microstructure including a span

of $37.5 \mu\text{m}$. **d** Optoelectronic act of SWCNT TCFs including the microstructure toward different A values of the lattice. Reprinted with permission from Ref. [125]

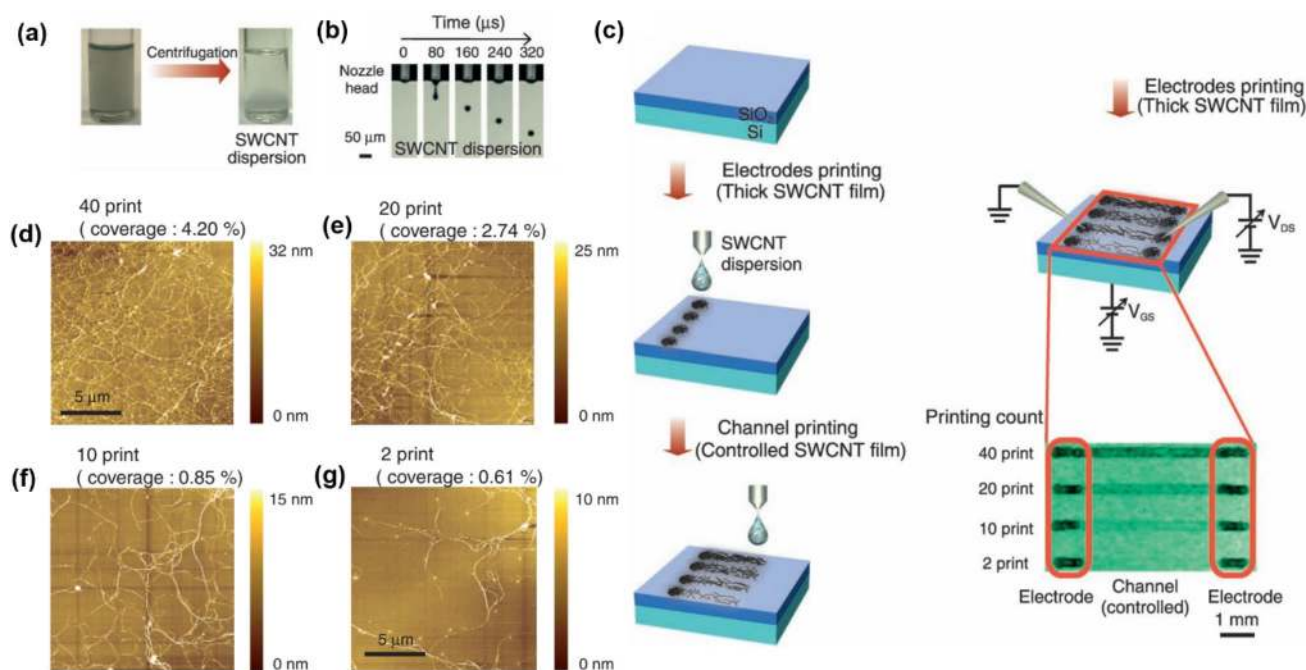


Fig. 6 Incorporation of inkjet-printed SWCNT-TCFs. **a** Visual microscopy picture of DMF-based SWCNT diffusion. **b** Photographs of a DMF-based SWCNT drop through inkjet print at a different time interval. **c** Representation of incorporation methods for inkjet-

printed SWCNT-TFTs. AFM pictures of the four kinds of systems formed with the removal of **d** 40, **e** 20, **f** 10, and **g** 2 prints/location. Reprinted with permission from Ref. [130]

the inkjet printing method (Fig. 6b). The physical features of SWCNT paint, including moisture capability and thickness, are generally equal to those of the real solution (*N,N*-dimethylformamide (DMF)) owing to the deficient absorption of SWCNTs. Figure 6c confers a representation of the substances, tool drafts, and incorporation methods. The SWCNTs are very large, that is typical of the laser extirpation process. Extended SWCNTs decrease the impact of transport leaping among SWCNT bunches and improve network movement. The sheet density was quite controlled and consistent. Further, the quantitatively studied the nanotube density of the particular four layers from the atomic force microscope (AFM) pictures (Fig. 6d–g).

Polymer-doped CNT thin films

The NP catalyst design may also be completed by the aid of the copolymer poly (styrene-block-acrylic acid) (PS-*b*-PAA) through micro-interaction print. In brief, a PDMS mould was plunged within a Fe-doped PS-*b*-PAA micellar suspension in toluene, attended with the physical alteration towards a silicon slice including Al_2O_3 layer through squeezing strain [132]. Beads of measured volume, configuration and surface chemical structure are proper construction blocks for forming template compositions including precise mesoscopic and nanometer ranges [133, 134]. Colloidal solubility of polymer beads [135] has also originated utilization including being

transporters to nanoparticles [136–138]. Dionigi et al. [139] published the feasibility of self-organizing distributed films of dissolvable organic semiconductors by polystyrene (PS) bead solution whose exterior is adsorbed by organic semiconductor bits using hydrophobic synergies. Polymer beads have been employed as supports to the displacement of SWCNTs and MWCNTs employing electrostatic synergies among the simple bead exterior and chemically transformed CNTs [140–142].

Figure 7 shows the different stages as CNT arrangement: **a** Spherical colloidal bit; **b** Polyelectrolyte doping; **c** Adsorption of CNTs; and **d** Extraction of the core. This construction method may be generalized to the arrangement of CNTs by varying diameter and expansion upon spherical bits of different dimension and type as supports. Models are displayed in Fig. 7e–g of catalyst colloids produced with the collection of one or more layers of CNTs, including various measures upon melamine, PS and silica balls. During all states, thick and consistent preparation was obtained, providing a reasonable restraint at the size of the nanocomposites by the number of films incorporated therewith [140].

The copolymer self-designed within round micelles including PAA regions inserted into the PS model following the deposition in toluene and this micellar layer worked as the pattern for producing Fe_2O_3 nanobunches. Oxygen plasma was utilized to extract the copolymer and moved the designed Fe_2O_3 NP substances upon the wafer. The spotted

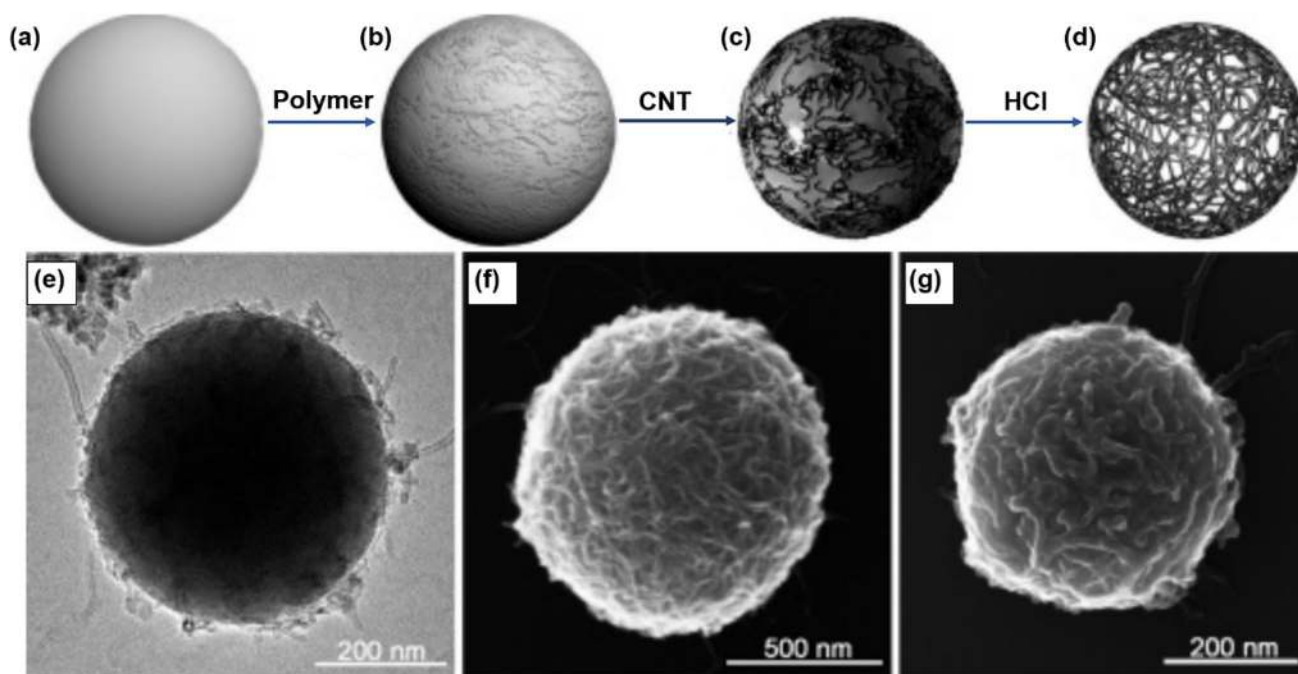


Fig. 7 a–d The several stages in the CNT device. e TEM of a silica bit (450 nm) covered by one coat of MWNTs; f SEM image of a PS bit (980 nm) covered by 2 coats of MWNTs; and g SEM picture of a

melamine atom (350 nm) covered by 3 sheets of MWNTs and coated by a surface coating of Poly (diallyl dimethylammonium chloride) (PDDA). Reprinted with permission from Ref. [140]

CNTs were developed by the decorated reagent bits through CVD.

Post-processes of CNT thin films

There are a few post-treatments systems depends upon transferring to determine the design of the CNTs. For instance, its low ion conductivity, O_2 plasma depended upon a potential linked plasma method has been applied toward designing SWCNT sheets at plastic support [143].

Iakubovskii [144] reviews primary methods of joining CNTs, each during the extension or through the post-extension processing. Several post-processing arrangement methods are explained, that apply mechanical stretching, separating, squeezing, friction, filtration, fiber design, the gas stream, liquid crystals, Langmuir–Blodgett method, magnetic and electric ranges. The post-processing further supports choosing nanotubes having a specific chirality [145]. Various post-extension methods of CNT arrangement are identified. This is not easy to judge them because several implementations have different specifications accurately. The integrity of mechanical elongating of polymer/CNT sheets and the Langmuir–Blodgett methods give them more proper toward investigation task upon CNT composites. The challenging job of the arrangement of single nanotubes over electrodes into single-tube machines may be taken with employing electric or magnetic domains. Scalability and

feasibility of automated or semi-automatic control choose fiber design, Langmuir–Blodgett and possibly gas flow systems toward manufacturing purposes.

Gao et al. [146] demonstrated the optimizing methods of soluble concentration and post-processing to forming SWCNT TCFs. FESEM images demonstrated the degree of dispersal of SWCNTs with sodium dodecylbenzene sulfonate (SDBS) and the bunch size within Fig. 8a–c. The white spots inside the pictures showed SDBS residuals and contaminants. TCFs handled beside nitric acid (HNO_3) showed that most abundant of the SDBS deposits were extracted and the rolled bunches grew flattened correlated by the natural SWCNT layers, as displayed under Fig. 8d–f. The elimination of non-conductive SDBS at the facade and among SWCNT systems improved the electrical performance of the SWCNT sheets.

The coated TCFs were next washed by deionized water to numerous times for eliminating SDBS connected at SWCNTs and dehydrated on $80^\circ C$ to 10 min accompanied with immersion into 12 M HNO_3 for 1 h and later cleaned beside lots of water for cleaning remaining HNO_3 and heated repeatedly. As shown in Fig. 8g the hydrophobic end alkyl chain group covered up for interfacing by the SWCNT exterior and compressed inside the bunch of SWCNTs owing through van der Waals force and a similar accumulating of the benzene circles upon the facade of graphite. In contrast, headgroup, including the hydrophilic sulfonic assembly,



may be suspended into water. Subsequent the layers were washed by water, piece of SDBS was withdrawn, omitting few remaining SDBS among areas of cells or adhering on the SWCNT exterior, as exhibited within Fig. 8h. While soaking TCFs into 12 M HNO_3 about 1 h, by Fig. 8i, protons were able to bond by the sulfonic assembly for improving hydrophilic feature of that extended alkyl series commencing toward gently softening into water. These covalent change associates over HNO_3 oxidative operations and offers in deficit positions with the SWCNT sidewalls conferring within Fig. 8j. The additional impact can be physical accumulation by which protons and NO_3^- can accumulate at the exterior of SWCNTs owing to a physical method conferring within Fig. 8k.

CNT TCFs amalgams

The chemical tie of CNTs is formed completely by sp^2 hybridization, alike to graphite. This type of bond is more potent compare to the sp^3 hybridizes within the diamond, and consequently provides CNT with exceptional durability. The thermal resistance of CNTs is expected chosen around 2800°C under a vacuity and about 750°C in the atmosphere [147]. Though, this is considerably changed during the fact of CNT TCFs. Incorporation is normally necessary for additional execution enhancement. The performance of CNT sheets may be exceedingly improved by chemically doping processing, which happens during the improvement of charge transport and reduction of junction stability of CNT-CNT contact. Still, incorporated CNT sheets convert sensible to air, heat and moisture. Therefore, the largest of the published characteristics of CNT-depend TCFs are not durable.

General doping

The sheet resistance within a chain of SWCNTs is restricted with the endurance in the SWCNTs and with the joint stability on tube-tube interactions, the following comprising the leading donor. Chemical doping is a crucial stage toward reducing both enrichment on the sheet resistances. Chemical incorporating improves the transmitter strength during semi-metallic SWCNTs, that lays out two-thirds of the SWCNT sheets. Several pieces of research reveal that doping also reduces the channelling block among SWCNTs and assume that it is the primary constituent into the complete film protection [148–150]. Strong acids, most generally HNO_3 , are standardly employed to dope the SWCNT sheets chemically [151–153].

While effective p-type doping, concentrated acids, and an inorganic solvent, for example, HNO_3 which includes SOCl_2 have been extensively utilized to manufacture CNT-based

TCFs including better performance. Jackson and his coworkers [154] orderly examined the resistance of with and without CNT-depend TCFs and shows the doping outcomes of HNO_3 are simply reversible, occurring in a sharp rise in sheet stability of doped CNT sheets. The evaporation of the acids commences toward sheet resistances those are sensitive above time and rises on values resembling these of undoped layers. The doping system usually includes the absorption of the CNT TCF within a dense suspension of dopant for some time or display to an environment toward volatile dopants.

Tulevski et al. [155] described the application of a particular electron oxidant (triethyl oxonium hexachloroantimonate, OA) toward chemically p-dope SWCNT sheets. The composite designs a charge-transfer system which includes the SWCNTs, involving dips in the SWCNT layer. Chemical doping is accomplished through the establishment of a charge-transfer network among the SWCNT and OA as shown within Fig. 9a. Figure 9b is an optical microscope picture of a partially thin sheet at a quartz disc. The AFM picture, exhibited within Fig. 9c, shows a permeating, interlocking system of SWCNT bunches, including diameters varying of 10–20 nm. The TEM (Fig. 9d) pictures show a layer which is clear of contaminants and wetting-agent, a consequence of both the trail gradient refinement round and an extended purification method. Figure 9e TEM picture of an SWCNT layer subsequent incorporating by OA. The composite adsorbs at the front walls and tube-tube intersections. Figure 9f is a structure of the transmission on the S22 zenith vs time toward together OA and HNO_3 incorporated sheets. The relationship between this visual and the electrical information within Fig. 9g is remarkable. It is a graph of σ/α vs time toward equally OA and HNO_3 incorporated sheets.

In general, the well-known chemical doping methods do not hold a great impact on the transmittance concerning the CNT sheets. While the visible light range, the transmission is sustained on an equal level while few dopants, for example, HNO_3 and SOCl_2 lightly enhance transmittance about 1.5 eV ($\sim 830\text{ nm}$). Though, the impact of chemical doping with these dopants does not stable because those fluid and volatile particles are poorly adsorbed at the surface of CNT and they can desorb. The durability of the doped sheets is more acute compare to the undoped equivalent, though the R_s are more profound than the untreated specimen. The poor durability will be a problem for industrial purposes.

CNT-based composite sheets

Preferably of chemical doping, the inclusion of another material with CNTs to develop a combination is a different approach to advance the activity of the sheets through merging the advantages of all the ingredients been utilized. The most broadly adopted substances comprise metal NPs and



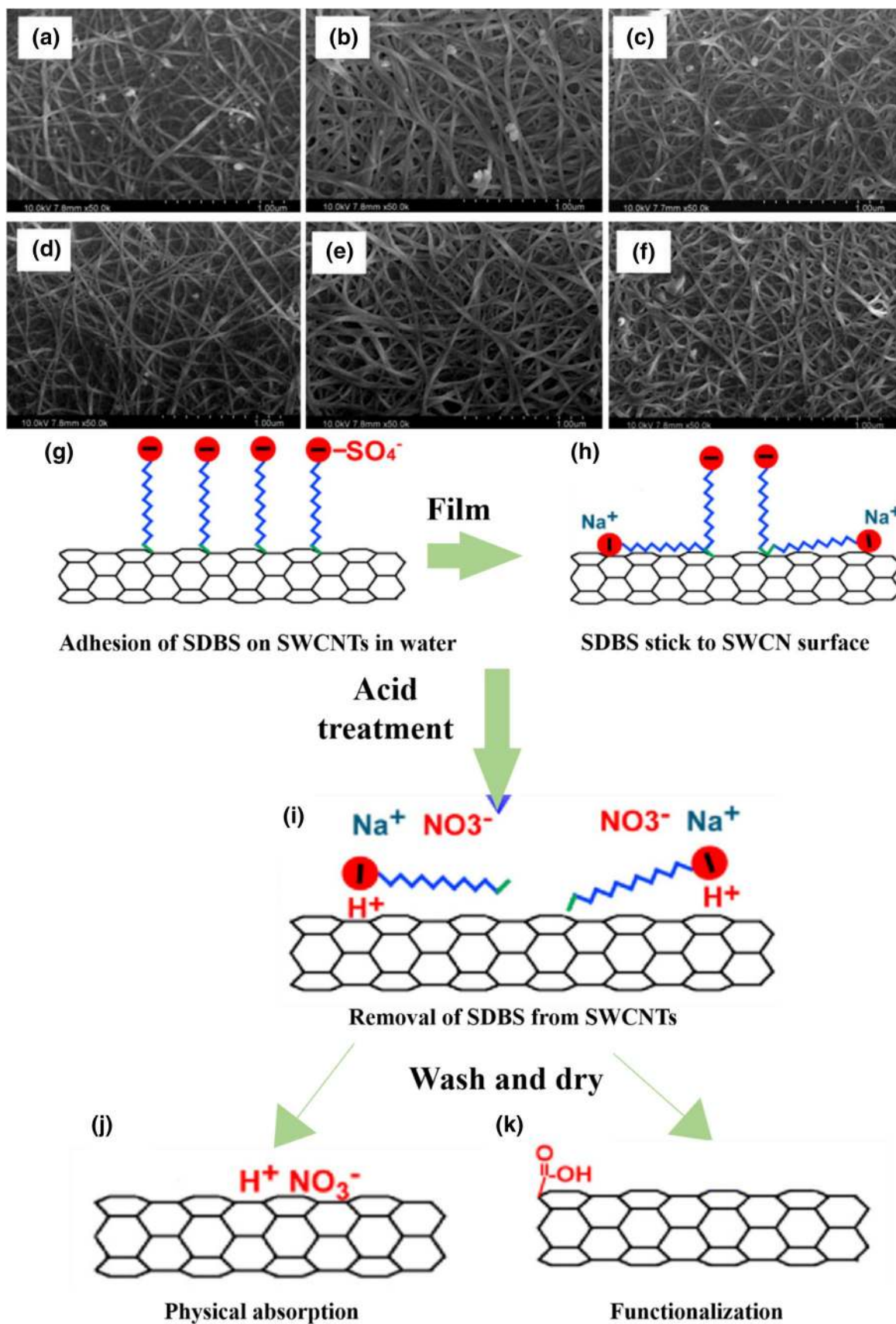


Fig. 8 SEM pictures of pristine **a–c** and following the HNO_3 processing **d–f** for the C/S mixing proportion of 1:5, 1:10 and 1:20, sequentially. **g–k** Diagram of how SDBS accumulated on CNT exterior and was transferred with HNO_3 . Reprinted with permission from Ref. [146]

NWs, CPs, and graphene. Nakashima et al. [156] adapted long double-walled CNTs (DWCNTs) as the original substance to incorporate transparent, extremely conductive CNT sheets. The long DWCNTs suspension denoted by D1. Figure 10 displays the images before (a) and later ultracentrifugation to 5 h (b) and 8 h (c) on 147×10^3 g, the powder within the picture (c). The uppermost 80% part of the buoyant (indicated D2) exhibited into Fig. 10c was obtained, and the powder was again dispersed by combining just water to achieve a suspension (called D3). The conductivity of DWCNT sheets on 94% transmission: incorporated transparent DWCNT layers at PET supports utilizing a wet coat (suspension disposition) process to D1, D2, and D3. For example, a standard SEM picture, diagram of a DWCNT and a picture of D3 layer are exhibited within the Fig. 10d, e and f, sequentially. Figure 10g–i exhibits the AFM pictures of D1, D2 and D3, by that estimated the distribution of their dimensions.

Table 1 displays a review of the optoelectronic characteristics of few picked CNT-based composite films.

Halide compounds for CNT thin films

Chemical alteration and incorporating are common approaches to improve the vector concentration and decrease the CNT-CNT junction stability under CNT systems. Dopants with halogen (Br_2) [171], strong acids [172, 173], metal chlorides [174, 175], metal NPs [176, 177], MoO_x [165], and organic particles [178] were broadly studied. Zhou et al. [179] have described a doping process for producing interrelating junctions in CNT materials among copper-halide (Cu-X) crystallites. Thin sheets of Cu-X may be made with both vacuum/solution-based methods. A vibration photonic preserving operation was practiced to provide fast warming and chilling method on a microsecond time range. This speedy heating and cooling method allowed the direction of Cu-X crystallites, that not only appeared during the production of CNT-CNT intersecting junctions although developed charge transfer doping. The photonic preserving method including improved constraints was produced to separate polymer scattered and form halide junctions. Those CuI crystallites were separately placed on the cross ends of two or more CNT bunches. Also, the new composition, incorporating with Cu-X expressively reduced the intensity of D-band signs. To explain the parts of the interconnecting halide junctions, the performance of CNT films in presence/absence of HNO_3 incorporating were also analyzed for

evidence. Possible uses need that the transparent electrodes should be durable [180].

The impact of incorporating was revealed during the echoing RS. The spectrum around $100\text{--}400\text{ cm}^{-1}$ is identified as the radial conscious form introducing from the responsive tube with the radial path (A_{1g} phonon). It gives a valuable report to the width and chirality of cells. On excitation energy of 2.41 eV, each of the semi-metallic nanotubes was induced into the primaevial specimen, as exhibited within Fig. 11a–c. The G-band arrived around 1590 cm^{-1} . The peak locations of the G-band have not moved noticeably on a low doping intensity equipped with 1 mM and were change up considerably with concerning 10 cm^{-1} on a high density. The result of improved p-type incorporating was also exhibited during the lightly enhanced energy of the G'-band around 2670 cm^{-1} , indicating extremely depraved p-type incorporating. A comparable appearance was recognized by various laser excitation (1.96 eV) demonstrated under Fig. 11d–f. Figure 11g confers the WF deviations received by the UV photoelectron spectroscopy and the sheet resistance on different AuCl_3 combinations. The potential Schottky limit among metallic and semi-metallic nanotubes is developed, as shown inside the representation of Fig. 11h. The connection resistance is dictated through a Schottky boundary established among the metallic and semiconducting nanotubes as exhibited within Fig. 11i, j–l) the intersection by improving AuCl_3 absorption [175]. AFM pictures of (m) as-dropped CNT, (n) CNT-CuCl, (o) CNT-CuBr, and at the other side, toward small range AFM (Fig. 11p), the dimension of CuI is also wholly reliant upon the thickness of CNT bunches. Cu-X was supposed to change the electronic and photonic characteristics of sp^2 -bond CNTs as p-type dopants, that were recognized through RS on $\lambda = 785\text{ nm}$ (Fig. 11q) [179].

Polymer-based conductive materials for CNT thin films

The facade environmental resistance is a matter including few metals and to apply by a compelling organic film. CP terminals may have a decreased or vacant exterior dipole limit to charge introduction correlated beside inorganic probes [181, 182]. Though CPs based probes, for example, polyaniline [183, 184] or PEDOT [185], do not communicate enormously visible light while layered indistinctly quite to be enough conducting. Reduced graphene oxide (rGO) probes, as less examined, need high-heat strengthening and are present regarding an array of degree too resistive [186–188].

One of the significant encouraging competitors for thin probes is the CNT system. The other is which straight dropped of CNT channels of the suspension has confirmed difficult owing to lower dispersal, heading toward non-consistent, ineffectively networked layers. Manufacturing



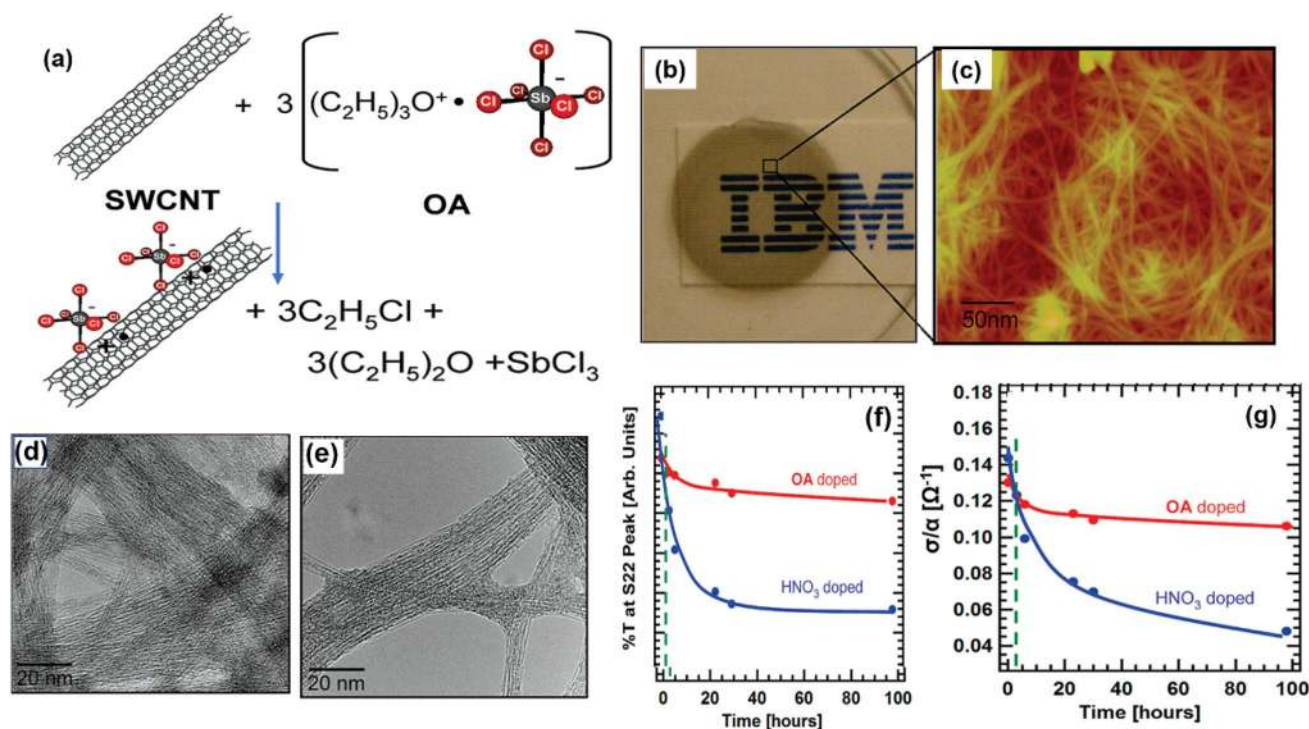


Fig. 9 **a** The reaction of OA with an SWCNT. **b** Optical microscope picture of an SWCNT sheet at quartz support. **c** AFM picture of SWCNT sheet showing an interlocking system of SWCNT bunches. **d** TEM picture of an as processed, refined SWCNT layer. **e** TEM pic-

ture of a film incorporated by OA. **f** Graph of %T on the S22 zenith vs time toward SWCNT layers incorporated by OA and HNO₃. **g** The graph of σ/R vs time concerning SWCNT coatings incorporated by OA and HNO₃. Reprinted with permission from Ref. [155]

the sheets at a vacuum filter and transporting them toward the needed support including the aid of wetting agents [189–191] and conjugated polymer [167] is the highest dependable procedure in current, generous greatest activity of 120^{-2} on 80% transmission undoped [189], 160^{-2} on 87% incorporated [191], or 80^{-2} on 75% under polymer compounds [167]; though the process standardly needs the usage of massive quantities of surfactant which requires to be excluded, and this gives sheets restricted toward the dimension of the film filter and includes a transfer print level. It is understood that CNTs are quickly scattered into chlorinated solutions under the appearance of poly-3-alkyl thiophene (P3AT), for example, regioregularity poly-3-hexylthiophene (rr-P3HT). Owing to the further conducting behavior of these polymers related by standard wetting agents as sodium dodecyl sulfate (SDS), and because of their capability toward scattering CNTs at inferior comparative absorptions, it can be expected that such sheets have excessive potential as consistent, TCFs.

Hellstrom and his coworkers [192] demonstrate an easy, dependable process toward developing consistent CNT system electrodes dropped right upon the exterior of concern by spin-coating or drop-casting. With interjecting conjugated polymers, for example, rr-P3HT or rr-P3DT on CNT dispersions into chloroform (CHCl₃), it significantly develops both

the scattering into a solvent and the essence of spin-covered CNT sheets at glass and polyethylene terephthalate (PET). Figure 12a confers the images of rr-P3HT: CNT composite suspensions, including different mass proportions within CHCl₃ subsequent sonication. Figure 12b composite sheets of various densities conforming spin-coating. The left picture displays a system about 89% transmission on 550 nm at PET. The right picture gives the identical sheet flat (bottom) along with two channels at the glass, of 92 and 87% transmission on 550 nm. The morphologies of rr-P3HT: CNT sheets diverge significantly being a function of corresponding mass proportion. A check solution comprising without polymer and 85 μg CNT/mL, spin-coated over the glass, has as discussed briefly a very inconsistent morphology, including compact sums of long tube bunches in few regions and scattered places within (Fig. 12c). While the rr-P3HT concentration enhances the appearance of apparent bunch sums both in suspension and on support decreases (Fig. 12a, d–f).

Entirely organic TCFs are more affordable, less poisonous, and resilient options over inorganic composite TCFs [193]. Polyaniline was practiced along with CNT in development of translucent composite sheets in early 1999 [194]. Further, PEDOT: PSS was applied to develop composite sheets including CNT systems [167]. The composite suspension was made by combining the standard ink of HIPCO

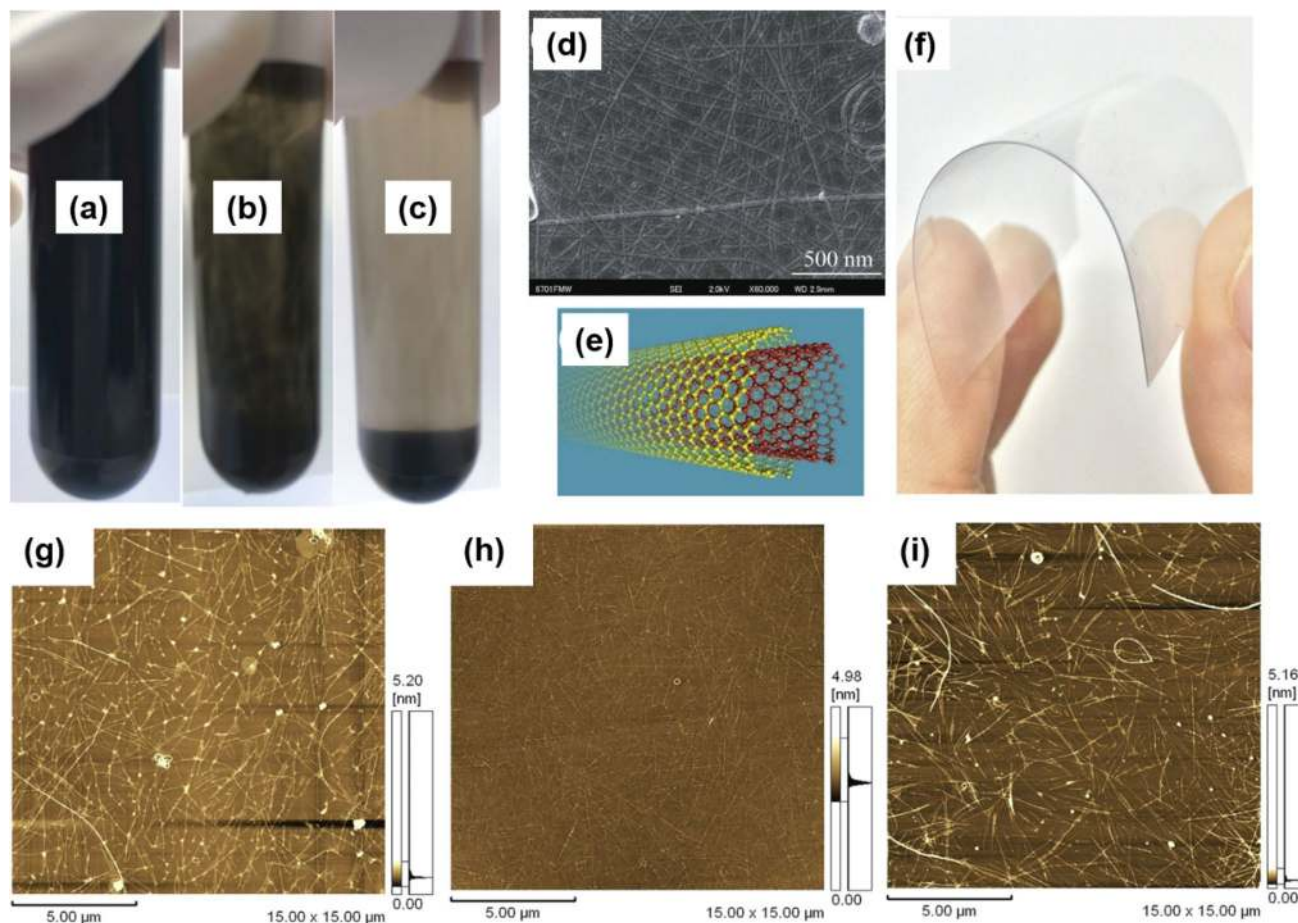


Fig. 10 DWCNT scatterings before **a** subsequent ultra-centrifugate (147×10^3 g) for 5 h (**b**) and 8 h (**c**). **d** SEM profile of a D3 DWCNT sheet. **e** Diagram of a DWCNT. **f** Picture of a D3 sheet. AFM profile

of initial specimen (D1) (**g**), supernatant (D2) (**h**) and scattering by powder (D3) (**c**) post-ultra-centrifugate 8 h on 147×10^3 g. Reprinted with permission from Ref. [156]

Table 1 Collation of TCOs and chosen CNT-based TCFs by the most suitable optoelectronic characteristics formed including distinct wet and dry incorporation processes

Preparation method	Ingredients	T (%)	R_s (Ω /sq)	σ_{dc}/σ_{OP}	Implementation	Refs
FCCVD	SWCNTs	90	84	41.5	Sensing board and LCD display	[157]
Roll to roll-dry	MWCNTs	83	24	82.7	Sensing board, LCD, and OLED display	[158]
Dip covering	SWCNTs	90	100	34.8	Sensing board and LCD display	[159]
Langmuir- Blodgett coating	SWCNTs	78	180	7.9	Sensing board	[160]
Brush painting	SWCNTs	79	286	5.1	Sensing board	[161]
Spin covering	SWCNTs	90	128	27.2	Sensing board and LCD display	[162]
Spray covering	SWCNTs	89	120	26.2	Sensing board and LCD display	[163]
Vacuum filtration	SWCNTs	83	30	64.4	Sensing board and LCD display	[164]
Spray coating	SWCNTs/MoO _x	85	100	22.3	Sensing board and LCD display	[165]
Filtration transfer	SWCNTs/AgNWs	84	20.9	99	Organic solar cells and OLEDs	[166]
Vacuum percolation	SWCNTs/PEDOT: PSS	75	80	15.2	Solar cells and displays	[167]
CVD growth	SWCNTs/graphene	96.4	300	34	Solar cells	[168]
Layer-by-layer transfer	SWCNTs/graphene	89	76	42	OLEDs	[169]
Spin-coating	PEDOT-SWCNTs	86	160	15	OLEDs	[170]



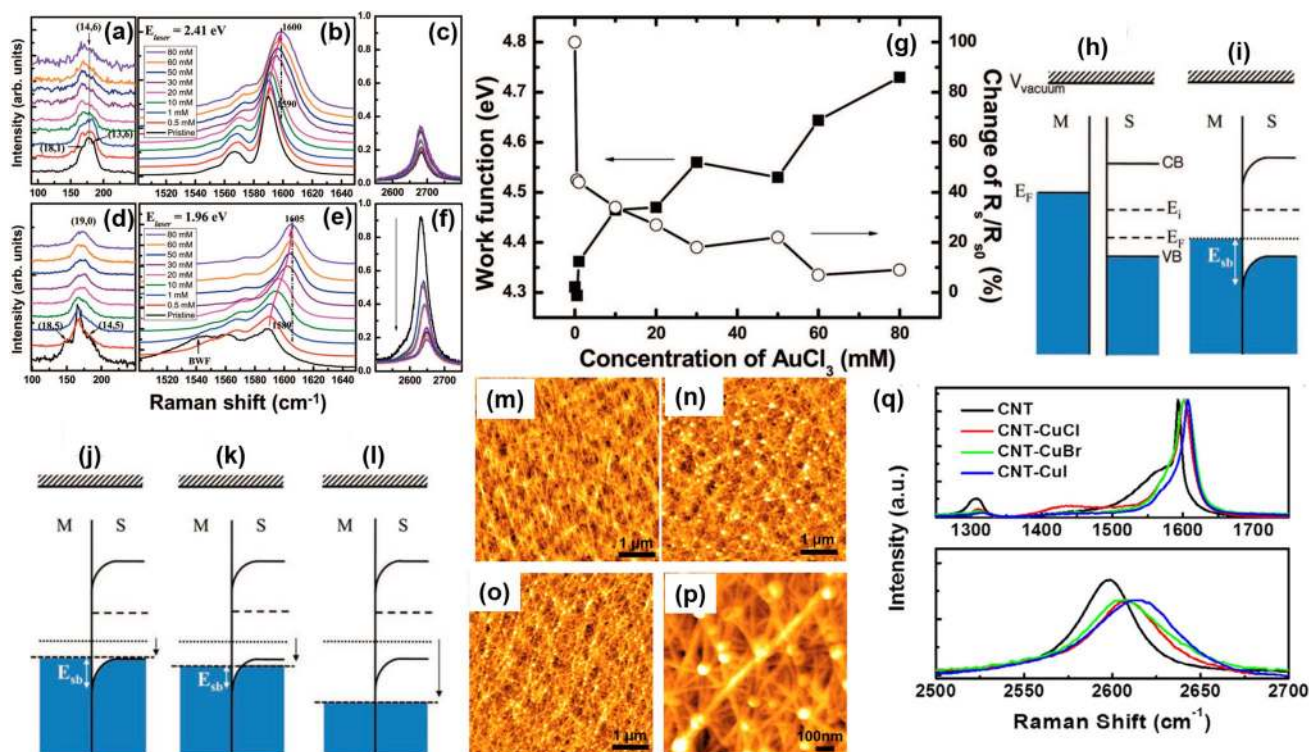


Fig. 11 RS of AuCl_3 -incorporated SWCNTs on excitation energy of **a–c** 2.41 and **d–f** 1.96 eV, sequentially. **g** WF and sheet resistance on different AuCl_3 absorptions. A representation description of the linkage formed among the metallic and semi-metallic SWCNTs into the SWCNT system by **h** a noncontact design, **i** the linkage into the pris-

tine specimen, and **j–l** the linkage by improving AuCl_3 concentration. Reprinted with permission from Ref. [175]. AFM pictures of **m** as-dropped CNT, and **n** CNT-CuCl, **o** CNT-CuBr and **p** low-range CNT-CuI layers. RS of **q** CNT and CNT-Cu-X sheets after the concluding fast thermic method. Reprinted with permission from Ref. [179]

SWCNT and solution of PEDOT: PSS and CNTs, developed through void percolation and convey toward resilient PET support below temperature and pressure. The sheets were moulded from an original range of curve of 7.5 mm to an ultimate radius about 2.5 mm earlier being unwound.

Graphene-based CNT thin films

Gr, an individual film of carbon, has been plugged toward its potential as an outstanding electrical driver following its test innovation during 2004 [195–198]. Gr is a CNT formed beside its axis and exposed to put flat surface. It may implement conduction roads over a larger area/unit mass compared to CNTs, that should turn in superior electrical performance on lesser optical thicknesses. The difficulty has been under grading up the mechanical splitting of graphite [199–201]. Individual film specimens are most frequently the outcome of a problematic peeling process, that is not scalable neither competent of generating consistent incorporations [202].

To design composite solutions of chemically changed graphene (CCG) and CNTs (G-CNT), GO [203], and partially oxidized CNTs were scattered instantly into anhydrous

hydrazine and permitted for stirring to 1 day, as exhibited within Fig. 13a. The spin rate had the maximum direct impact upon transmission, as is manifest inside the images and profile showed within Fig. 13b, c. As assumed, higher spin rates produced more translucent sheets which were further optically translucent, including the accumulated on 1050, 1250, 1500, and 1750 rpm demonstrating optical transmissions about 58, 70, 87, and 92%, sequentially. Four-point sheet resistance analyses were performed at similar tools after incorporation of tiny gold fingers. Figure 13d presents the relation in spin rate and sheet resistance.

The same designs have been published utilizing vapor rGO as the base probe, however high resistivity was harmful toward solar cell activity, i.e., decreased short circuit flow and fill aspect occurred during a power regeneration performance about 0.2%. The tool arrangement and performance properties of PV designs are exhibited within Fig. 13e, f. Chemical doping has been extensively examined, being an efficient technique toward improving the conductivity of CNT probes. Facile approach beside SOCl_2 vapor is usually used by way of anion incorporating and does not suggestively influence the optical transmission of CNT sheets. The same approach for the hybrid operation by revealing



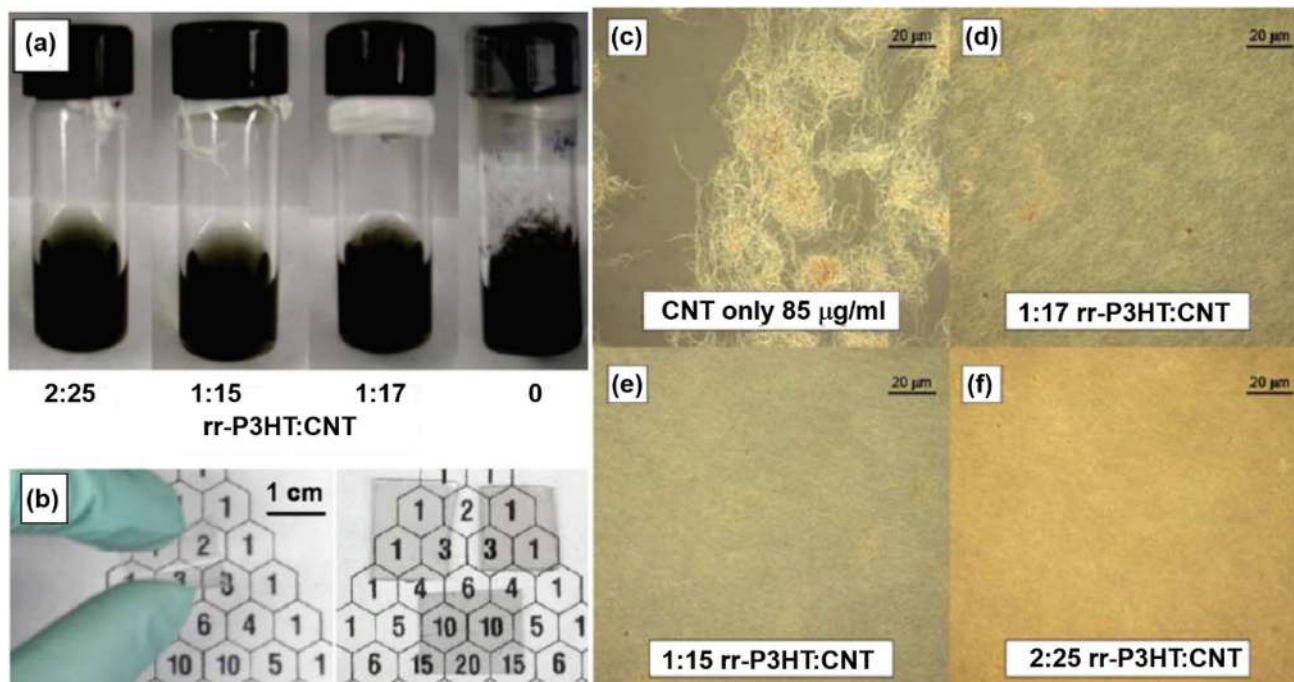


Fig. 12 Images of **a** rr-P3HT: CNT composite solutions including different weight proportions into CHCl_3 subsequent sonication and **b** composite sheets of various concentrations resulting spin-coating. **c** Visible micrograph of a nanotube system upon glass, of around 76% transmission on 550 nm, spin-coated by an 85 g/mL CNT suspension

in CHCl_3 in the absence of polymer. **d–f** Indistinguishable micrographs, spin-coated by rr-P3HT: CNT complex suspensions in CHCl_3 bearing the designated corresponding weight proportions. Transmissions at 550 nm are 79, 80, and 83%, sequentially. Reprinted with permission from Ref. [192]

as-incorporated G-CNT sheets to SOCl_2 fumes following spin-casting. The sheet resistance and subsequent processing are reported within Fig. 13g [204].

To utilize the advantages together of graphene and CNT, entirely carbon TCFs were developed, where CNTs work as the connections to join the graphene films [205–208]. CVD is a general approach to incorporate great single-layer graphene including a more transmission around 97.7% by R_s near $\sim 1 \text{ k}\Omega \text{ sq}^{-1}$ [209]. Based on this approach, a facile method was summarized by Kim et al., [168], also it included the solution-based doping of SWCNT upon Cu foil via spin-casting.

Advantages and drawbacks of Gr and CNTs Gr is a thin film of carbon particles designed under a hexagonal composition, or a flat single film of carbon atoms which are tightly bound within a 2D honeycomb structure is the ‘new phenomenon substance’ which is supposed to fashion around all phases of prospective technologies. Being as the single 2D construction upon the earth a much is assumed of this matter [210–212]. Then the nanomaterial’s, for example, the CNTs, including novel electrical, mechanical, and surface characteristics, have caught the recognition and excited the attention of several investigators. CNTs are a vast part of technology, and unique applications toward them are being

discovered each day [213–215]. Though, both materials do have its advantages and drawbacks as presented after this in Table 2.

Implementation of CNT-based TCFs

TCFs are broadly accepted in the regular day concerning different optoelectronics applications. Although ITO is controlling the modern era in effective utilization of TCFs, more exceeding financial results employing ITO options including CNTs, metal screens along with metal NW are resembling. In this segment, we examine current development and explain the hurdles in sensing devices, OPV also OLED materials that can practice for CNT-based TCFs.

Sensing panels

Sensing panels, i.e. information tools at the head of electronic screens, are the more broadly utilized sensing tools. Touch devices have been broadly utilized as a primary human/machine interaction medium in different digital tools, for example, tablets and smartphones, and need toward them is quickly developing. A resistive sensing device comprises numerous films, the most notable of

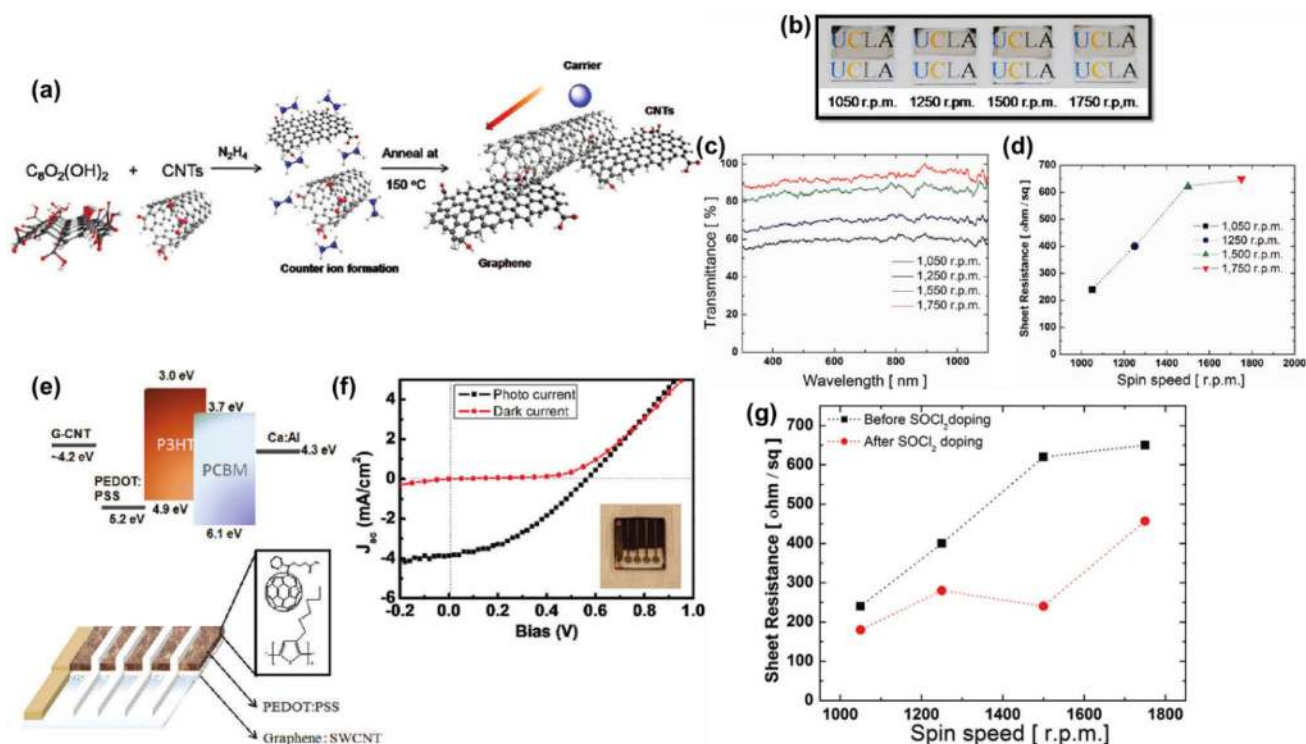


Fig. 13 a The schematic method to compose hybrid solutions of CCG and CNTs. The images and UV–vis spectra exhibited inside (b and c). d Reveals the correlation in spin speed and sheet resistance. The tool

arrangement and performance properties of PV devices are exhibited within (e and f). The sheet resistance here and subsequent processing are shown into g. Reprinted with permission from Ref. [204]

Table 2 Advantages and drawbacks of graphene and CNTs

Graphene	Carbon nanotube
<p>Advantages:</p> <p>This is the most delicate material recognize, including that also the most effective</p> <p>It contains an individual film of carbon atoms and is both flexible and translucent</p> <p>It is an excellent conductor of each temperature and power</p> <p>It is employed within the generation of high-pace electronic tools capable of swift technological innovations</p> <p>Chemical sensors useful on identifying ammunition</p> <p>Membranes toward the higher effective filtration of gases. Films by that nano-range holes form those membranes have been built</p> <p>Transistors which work on greater frequency than that of others</p> <p>It has directed toward the generation of lesser prices of display screens inside mobile designs with substituting indium-dependent electrodes into OLED that also more economic power dissipation</p> <p>Employed during the generation of lithium-ion batteries which restore more active. These batteries practice graphene at the anode covering</p> <p>Drawbacks:</p> <p>As an excellent conductor of power, though this doesn't have a band-gap. Investigators are managing upon amending this</p> <p>The main drawback of graphene being a catalyst is its sensitivity toward oxidative circumstances</p> <p>The investigation has confirmed that graphene shows some toxic properties. Experts observed that graphene emphasizes rough sides which can quickly penetrate cell membranes, enabling it to insert in the cell and disturb regular functions</p>	<p>Advantages:</p> <p>Very small and lightweight, presenting them attractive substitutes to metallic filaments</p> <p>Sources needed to create them are abundant, and several may be done with only a little quantity of substance</p> <p>Are resistant on temperature variations, indicating they function nearly quite as great in the excessive cold as they appear in intense temperature</p> <p>Have been into the research & development (R&D) stage toward a long time instantly, suggesting most of the difficulties have been functioned out</p> <p>As the latest technology, investors have been accumulating in these R&D organizations, that will promote the cost-effectiveness</p> <p>Drawbacks:</p> <p>Notwithstanding whole the investigation, investigators yet don't realize precisely how they control</p> <p>Notably small, therefore tough to run with</p> <p>Presently, the method is comparatively costly to provide the nanotubes</p> <p>It would be costly to execute this innovative technology into and substitute the earlier technology during all the areas which we could</p> <p>At the rate our expertise has been growing antiquated, this can be a risk to trust in this technology</p>

those are two films of TCFs divided with a tiny space, though a capacitive sense board includes a nonconductor and a film of TCF [216]. Resistive sense devices normally require TCF including more leading transmittance (> 95%), but capacitive sense devices require TCF including lesser film resistance ($< 300 \Omega \text{ sq}^{-1}$). Touch boards don't have specific necessities towards exterior coarseness or the WF of TCFs, including the necessity toward film resistance is not stringent. Touch boards are one of the utmost encouraging possible uses for CNTs-based TCFs [217–219].

During all three varieties of units, for example, CNTs, PEDOT: PSS, and composite (i.e., PEDOT: PSS-doped CNTs), the film resistance (R_{sq}), and visible transmittance (T_{vis}) were included. The consequences are described in Fig. 14a toward CNTs (C_x) along with the improved spray period by 20 s (C_1)—80 s (C_7) moreover, Fig. 14b for PEDOT: PSS sheets (P_y) conferring to the reduced spin rate by 1500 (P_1)—200 rpm (P_7). Figure 14c exhibits the effects of R_{sq} and T_{vis} estimated by the different composite sheets (C_xP_y). For example, the C_3P_5 unit was formed by spreading the PEDOT: PSS layer (P_5) during the spin rate of 300 rpm on the dropped CNTs (C_3) by 40 s of spray period [218]. Though, another low-cost technology with metal mesh and metal NWs is also drawing risen recognition. Hence, besides

the activity of transmittance/film stability, the cost is growing a significant part in the selection of TCFs.

Organic photovoltaics (OPV) devices

Organic photovoltaic (OPV) cells are an encouraging applicant being as energy reserve toward the coming period. Though, the performance of the OPV cells should be developed to effective treatment. The unique explications toward the development of competence into OPV cells are the employment of a tandem arrangement, that receives light from a broader spectrum. The tandem OPV (T-OPV) cell is typically arranged as a set of cells in a chimney [220–222]. Hiramoto et al. [223] composed a T-OPV cell utilizing a set bond and an ultrathin Au film among two-unit cells exhibiting an improvement within the entire open-circuit voltage (V_{OC}).

Tanaka et al. [224] practiced the transparent film of bathocuproine (BCP) being the exciton-hindering sheet into the backbone cell. The front and upper pictures of a representation formation of a consistent T-OPV are displayed within Fig. 15a, b, sequentially. For the identical relationship, Al and ITO probes were combined through an outer circuit and were practiced to electron accumulation, although the MWCNT film is employed as a hole assembling

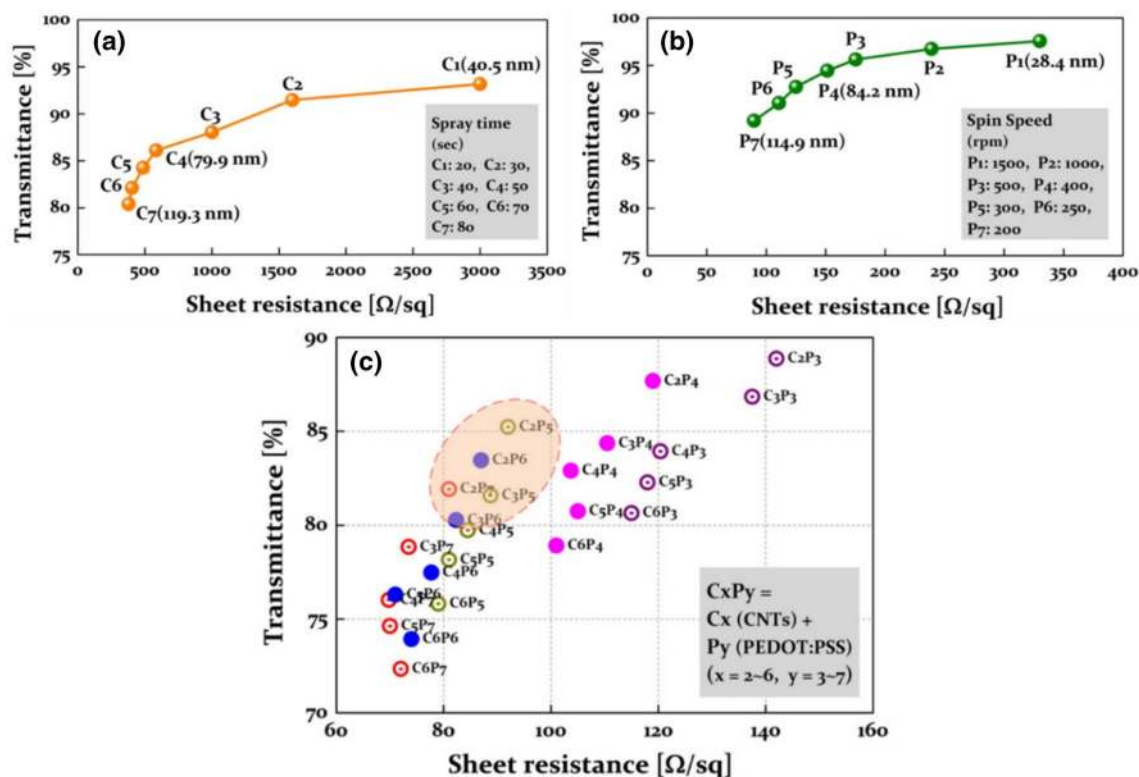
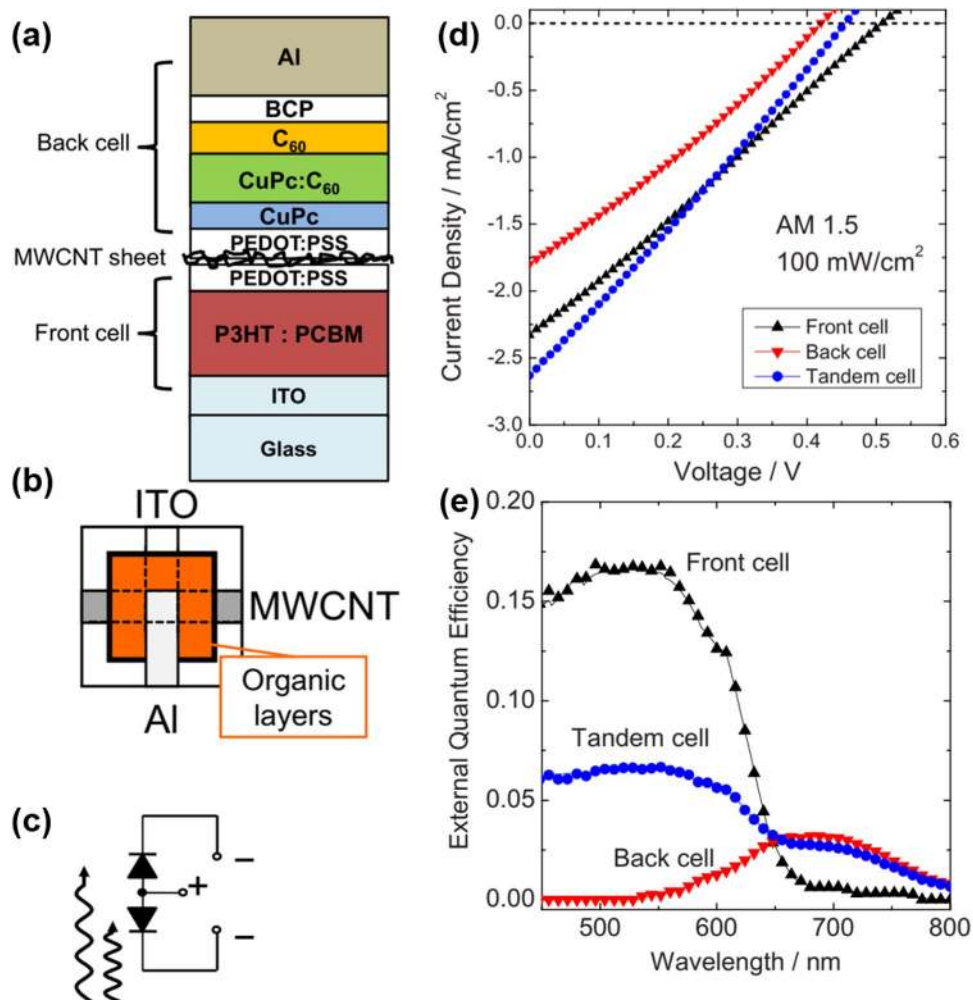


Fig. 14 The estimated T_{vis} and R_{sq} : **a** for CNTs as a function of spray period, **b** to PEDOT: PSS being a function of spin rate, and **c** towards PEDOT: PSS-doped CNTs as a function of an aggregate of CNTs including PEDOT: PSS. Reprinted with permission from Ref. [218]

Fig. 15 The schematic machine formation of the uniform identical T-OPV cell. **a** Cross-section look of shapely films, **b** Top appearance of a standard T-OPV cell and **c** Equivalent circuit. **d** Photo-*J-V* properties of the standard parallel T-OPV alternative cells toward the leading cell, back cell, and the entire tandem parallel nexus. **e** Wavelength relationships of photocurrent toward the front, back, and the parallel juncture cell. Reprinted with permission from Ref. [224]



probe. Figure 15c presents the representation equivalent circuit. Inside Fig. 15d, standard photo-*J-V* properties of the T-OPV cell are exhibited. To the T-OPV cell through the identical joint, the ITO and Al external probes were utilized as an electron-assembling probe, while the central interlayer MWCNT film was accepted as a hole-gathering probe. Figure 15e gives the wavelength dependency of the surface quantum power concerning every cell. During all analyses, quantitative calculations were not implemented because of the uncertainty of the total worth of the photocurrent, perhaps effected via air contact while the estimations.

OPV cells with heterogeneous perovskite photovoltaics have brought considerable attention toward educational and industrial areas, owing to their potential being an encouraging origin of renewable energy. In the last few years, notable growth within OPV cells has been completed with the expansion of particles and tool incorporation methods. Though, those attempts have principally been taken out at ITO painted glass supports. The fragile ITO sheet is not suitable for prospective OPV cells, that would be adaptable at plastic supports to distinguish them by traditional crystalline

Si PV cells. Hence, discovering the fib method on soft electrodes is of prominent interest in promoting OPV cells to everyday usage. In OPV operations, CNT sheets can work being the transparent positive electrode [225], the cathode to produce a reversed composition [226], and an optional substantial of the base electrode toward ores [227], moreover as a backup to the oxidative metal probe (usually Al including Ag), that serves to be included within the tarnish method at the environment comprises sulfide sorts, nitrogen dioxide, plus ozone.

TCFs for OPV cells require quite lower sheet resistances coupled beside high clarities, to stop a higher range resistance whereas providing the photons to enter the working sheet. To develop the soft OPV cells, the PANI: CNT sheets were placed up plastic (PET) support and accepted as transparent probes.

Organic light-emitting diodes (OLED) devices

A conventional OLED has two terminals (positive and negative), amongst that it is the releasing sheet comprising



electroluminescent substance (normally by the electron-carrying and hole-carrying films) which may generate light in rejoiner to potential-induced electric flow [2]. To validate the activity of SWCNT TCFs, Jiang et al. [228] fabricated a soft phosphorescent greenish OLEDs which were utilized as produced SWCNT TCF being working electrodes. Figure 16a exhibits the optical picture of a bright SWCNT OLED, including an around 5-V accumulation, which proves intense and consistent green luminescence. Figure 16b displays the electroluminescent representation of the OLED, beside the highest luminance about 4088 cd m^{-2} and a switch-on potential about 2.5 V. This lower turn-on potential is associated with the high optoelectronic property of our SWCNT TCF. Figure 16c shows the relationship between current and power efficiency vs luminance. The highest current and power efficacies are 75 cd A^{-1} and 89.5 lm W^{-1} , sequentially. Moreover, the SWCNT OLED exhibits an attractive exterior quantum yield of up 15% (Fig. 16d).

While potential is employed among both electrodes and the negative charges (e^-) are introduced in the LUMO stage of the cathode surface, this e^- are removed at the HOMO stage on the anode surface as a consequence of the almost positive energy within the electron moving, blowing, and hole-carrying films. OLED is drawing progressively attention in compact-state igniting patterns and digital screens in designs, for example, a television display, a computer screen, and several compact tools. OLED is a light-releasing diode, at the emissive electroluminescent film is an organic layer which changes electrical flow into the light. This organic layer is crammed by two probes, from them one is translucent. Assessing the potential of CNTs as the foundation of approaching nanoelectronics processing, which has become a hot topic of the intensive investigation after their invention. Now significant investigation toward macro-optoelectronics has concentrated at improving the execution of OLEDs with doping CNTs within polymer patterns as a dopant substance [229–232]. This is affirmed that the succession of

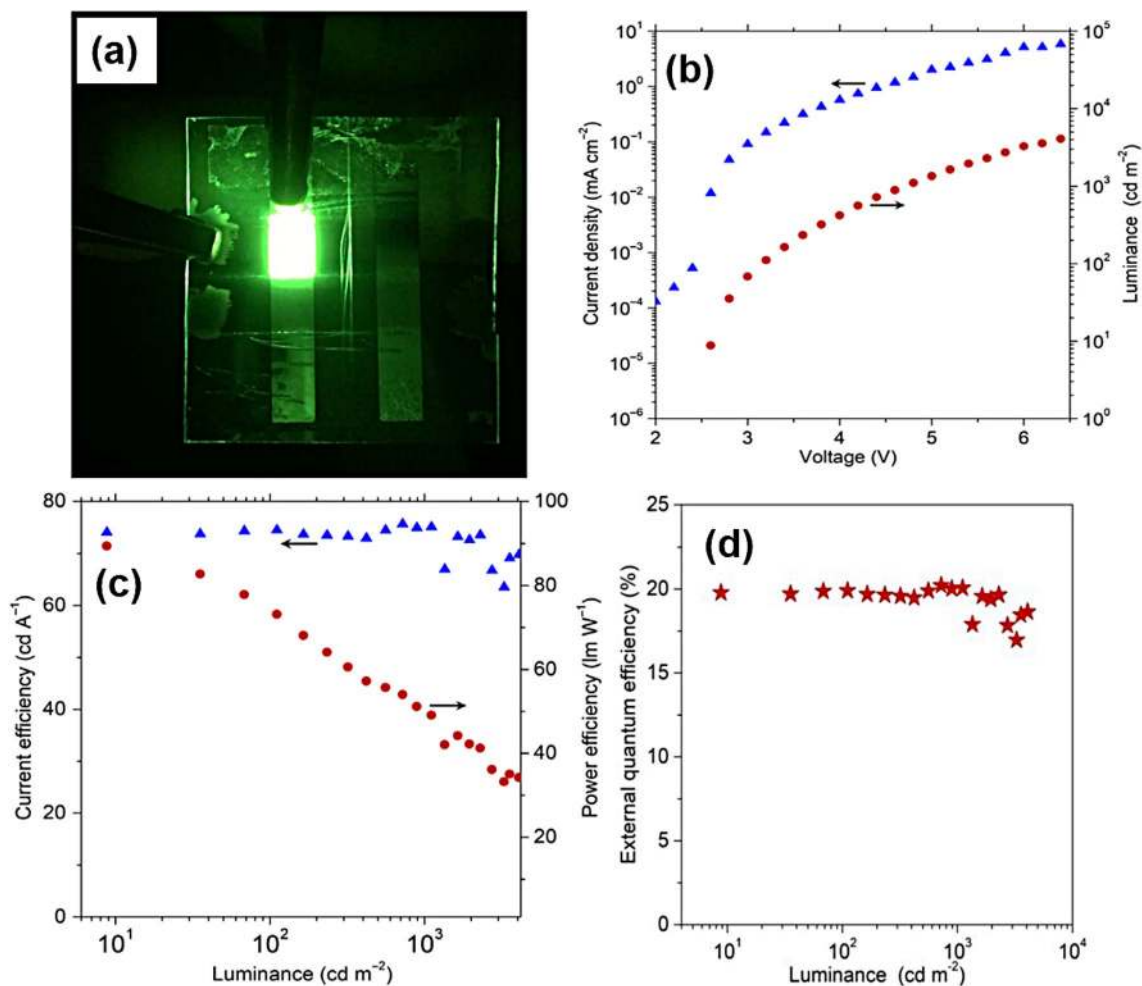


Fig. 16 **a** Optical photograph of a lighted SWCNT OLED. **b** Current density and luminance vs potential. **c** Current and power efficiency vs luminance. **d** External quantum efficiency vs luminance of the tool. Reprinted with permission from Ref. [228]



CNTs including polymers gives an engaging way not just toward strengthening polymer sheets, moreover also to the injecting novel electronic features based upon the morphological alteration of electronic synergy among the two main ingredients.

Zhou and his coworkers [191] presented a comparable investigation on TCFs produced by two varieties of industrial CNTs: HiPCO and arc-removal nanotubes toward OLEDs at both hard glass and stretchable supports. A picture of the developed tool (at glass support) is displayed within the upper-left inside of Fig. a. Figure 17b displays the photoluminescence (PL) profile of Alq_3 , including a solitary peak positioned on 520 nm. The PL profile of the OLED was listed within Fig. 17c. The current density (CD) obtained utilizing a tool area about 2 mm^2 , explained monotonic but nonlinear progress by the potential prejudice and gives 0.7 mA cm^{-2} on 20 V. An improvement into illumination was followed, including growing CD, gave a start potential of 5 V and a shine of 17 cd m^{-2} on 20 V (Fig. 17d). Figure 17e outlining the quantum performance as a function of potential prejudice, that ranged within 0.21% and 0.34% in a broad bias scale from 0.6 to 20 V.

Hence, CNT-based TCFs have now attained remarkable progress in a series of applying on a laboratory range. It can be utilized during the incorporation of a series of solar cell structures, sensing devices, OPV cells, and OLEDs. Though, there are yet some points to mark for every one of certain purposes. However, CNTs have incredible durability under a few strict circumstances, few other ingredients into the hybrid, for example, the PEDOT: PSS, undergo from low

durability in heated or moist climates. Moreover, incorporation methods could be needed for long-term prospects.

Thin-film transistors

Recently, the advancement of solution-prepared high clearness SWCNT substances [233, 234], uniform system class CNT sheet including exact tube density is possible upon large area supports [235–238], that promotes the advancement of high-performance CNT thin-film transistors (CNT-TFTs). TFTs are essential electronic components, for example, screen panels, Radio-frequency identification (RFID), Printed circuit board (PCB), electric sensors, and so on. Comparatively complex circuits based upon CNT-TFTs, like Ring oscillator [239], sensor system [240] and complementary metal oxide semiconductor (CMOS) type 4-bit complete adding machine [241], have been described at both stiff and stretchy supports. This progress displays the exceptional commitment of the CNT-TFTs upon coming macroelectronics. Huang et al. [242] found that ambipolarity suppression systems employed within FETs at unique CNTs do not serve appropriately upon the CNT-TFTs. In that study, by joining the asymmetric gate pattern and chemical incorporating approaches, high on/off proportion ($> 10^3$) was obtained on open origin/drain preference into CNT-TFTs including approximately small channel dimension and thin high-k gate dielectric combination.

Li and Zhou [243] reported the transfer curves below various consumption-source preference and capacitance-current following 10 kHz were estimated toward each carbon-based

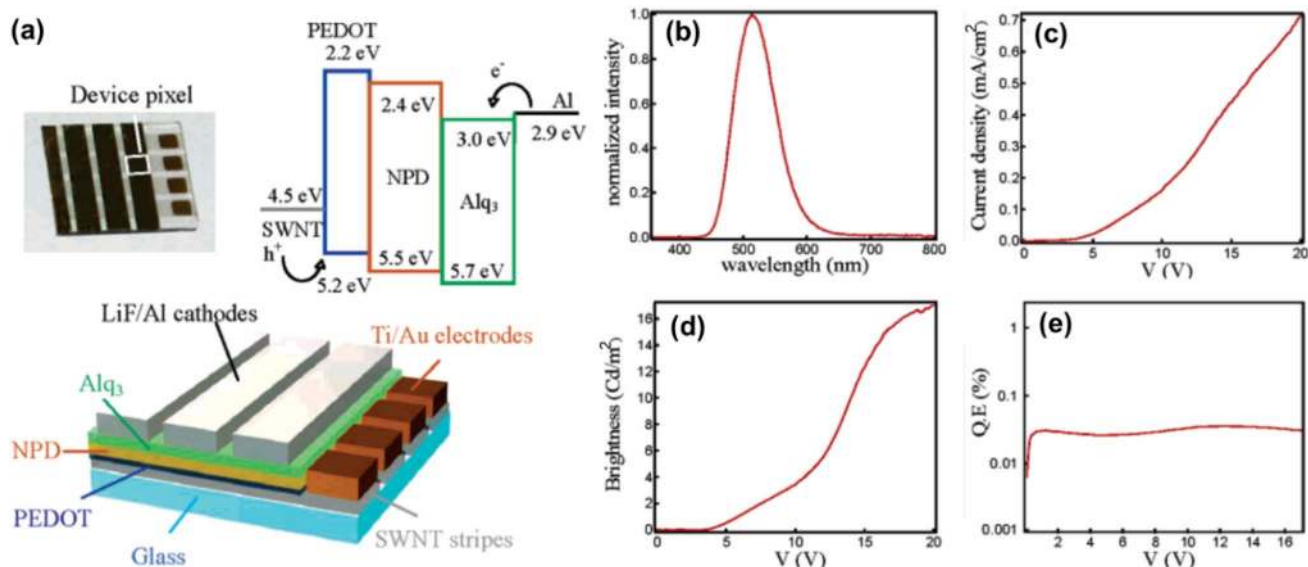


Fig. 17 a Arrangement of the OLED apparatus contains several sheets of designed SWNT coating. b PL profile of the Alq_3 layer. c CD vs potential bias profile registered at one tool pixel. d Brightness

vs potential bias. The tool displays an inception potential about $\sim 5 \text{ V}$ and the highest brightness of 17 Cd/m^2 . e Quantum efficiency as a function of CD. Reprinted with permission from Ref. [191]



CNT-TFTs including SEBS dielectrics and substrates. Shiheng et al. [244] demonstrated a homogenous and steady aerosol jet printing of CNT-TFTs by an ink temperature controller which generates designs displaying space movement of $\mu_h = 12.5 \text{ cm}^2/\text{V}\cdot\text{s}$ including a comparative standard variation as inadequate as 4% (of above 38 patterns). SWCNTs have been broadly investigated during several potential purposes, for example, TFTs, solar cells and sensors due to their outstanding electronic characteristics. SWCNTs dependent sensors have the latent chosen printable, economical and compact, and the high exterior area of SWCNTs allows shallow disclosure boundaries. Greatest SWCNTs are exhibited as a hybrid of metallic and semiconducting (sc) CNTs, and as such mostly SWCNT sensors have accepted these compounds [245, 246].

Hong et al. [247] investigated a lower-current microwave annealing (MWA) method to developing the electrical properties of irregular CNT-based TFTs and diode-load inverter circuits in the absence of thermal disturbance. The lower-current MWA method was used to post-accumulation annealing toward eliminating deficiencies and charge traps in CNT TFTs and contrasted, including conventional thermal annealing (CTA). The outcomes showed that the lower-current MWA treated tools had excellent electrical properties and method yields compared to the CTA-processed systems, on the similar operation heat. While the annealing temperature of the CTA-processed equipment grew, thermal loss happened within the CNT channel film, heading toward a decline into the machine yield and degeneration of the electrical properties. The feature of the printable dielectric film has grown one of the significant barriers toward obtaining high-performance entirely printed conductors. A compact dielectric film will need high gate voltage to turn the transistors on and off, that will induce high energy radiation into printed tools. In rejoinder to this difficulty, entirely printed CNT-based TFTs have been incorporated at flexible layers, for example, polyimide and liquid crystal polymer utilizing aerosol jet printing [248].

Figure 18a exhibits an s-SWCNT band into a centrifuge cell after two repetitions of density gradient ultracentrifugation (DGU) of CNTs generated through arc-discharge. The relevant content of s-CNTs is determined selected 99% through analyzing the comparable area below the metallic and semiconducting zeniths during the optical absorbance graph, and TFTs based upon such distributed CNTs obtain concurrently high conveyor flow, transconductance and on/off proportion. Figure 18b exhibits an efficient gel chromatography process for understanding the large-range single-chirality division of CNTs, that is much easier compared to the DGU process. A novel ion-exchange surface chemistry method toward the position of single CNTs into a high density (Fig. 18c), under that CNTs, was selectively placed at HfO_2 areas covered with a single surface film which includes

a hydroxamic acid edge collection self-accumulating at HfO_2 facades, but not upon SiO_2 [249] (Fig. 19).

Bio-organic interface

Hybrid interfaces among existing cells and organic conjugated polymers perform a crucial part in bioelectronics medication. In recent years, conjugated polymers are broadly used toward optical stimulation of existing cells and different bio-interface purposes, for example, neural investigations, cellular structures and biosensors toward drug discharge [250–252]. Moorthy et al. [253] examined a mixture of S-SWCNT/C₆₀ substances accumulated above graphene optically transparent electrode, that is also recognized as G-Optrodes is admitted toward general biological. To discover the spectral effect, structural, electrochemical resistance, thermal endurance and toxicity, to the evaluation of these substances as an efficient and competent bio-optical interface.

During current years, multielectrode arrays (MEAs) have grown a comprehensive mechanism toward interfacing, including neural devices for each stimulation and record objects. CNTs seem to be the most proper interface substance to these applications because it is chemically inactive, sturdy upon mechanical loss and calm to manufacture. Besides, high-density CNT-covered surfaces are identified through having a remarkably large surface area [254]. Greatest fascinatingly, CNTs seem to promote neuronal outgrowth. Based on that Shoal et al. [255] examined the appropriateness and the potential benefits of CNT MEAs to retinal implant treatments. This is proved by utilizing electrophysiological records from whole retinal mounts that CNT electrodes guide toward more reliable electrode-tissue coupling, producing in unprecedented signal-to-noise proportion. The capability toward interface tissue cells, including new (nano)materials able to efficiently change the electrical performance of the whole neuronal system presents unique methods into neuroscience investigation and prospective purposes under neurology and neuro-prosthetics. In this class, CNTs are recognized and extensively investigated CNMs and, gratitude to their widely studied physicochemical and biological characteristics observed use within various areas varying of biology to nanomedicine [256–259]. Rago et al. [260] showed that CCVD could quickly create a homogenous and patterned matting of real MWNTs at holding silicon supports as highlighted with an aggregate of electron microscopy and spectroscopic methods. Consequently, consistent CNT rugs were practiced as promoting supports to the growth of neuronal systems from rat hippocampus initial cells. Wang et al. [261] demonstrated a possible approach to trace the in vivo degeneration of zein-based biomaterial. Zein being a novel bone replacement



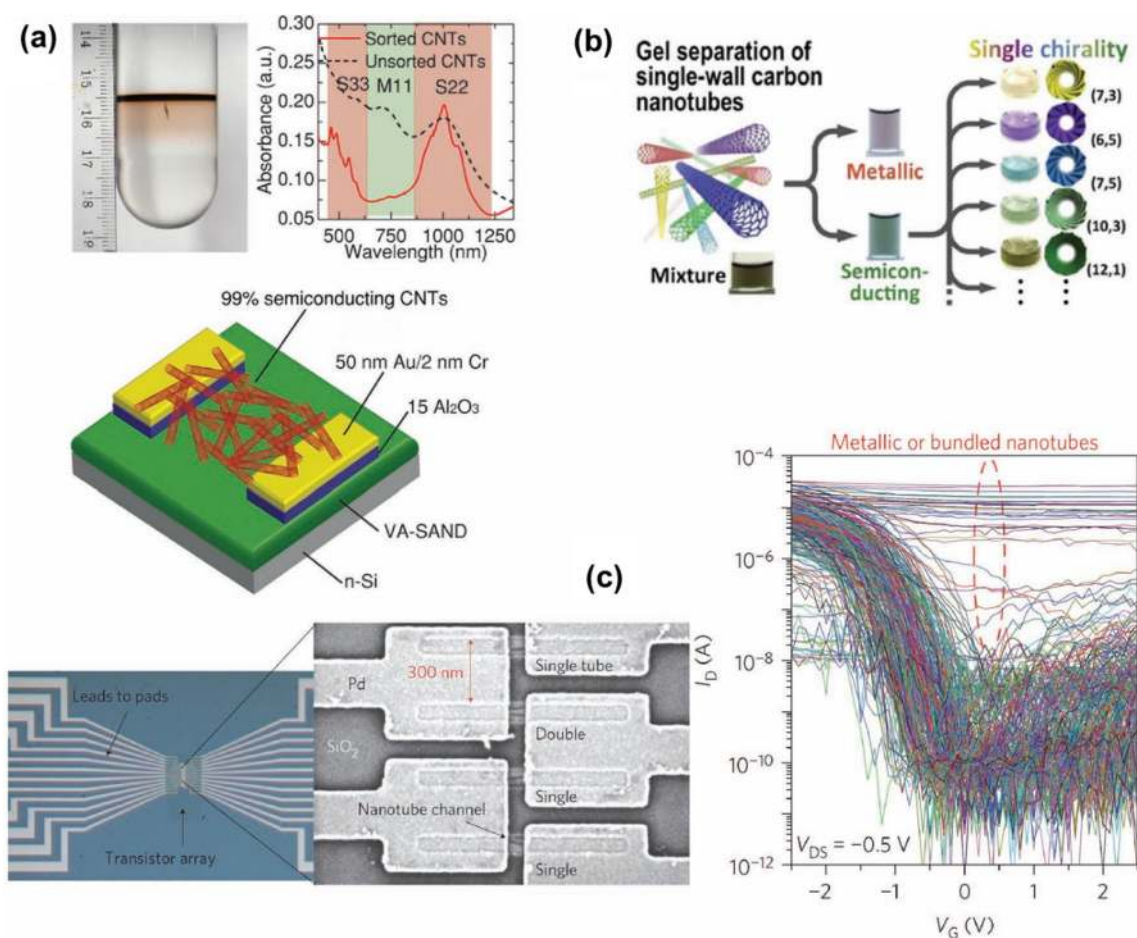


Fig. 18 CNT solutions to design substance arrangements toward stretchable electronics. **a** A 99% classified semiconducting CNT unit practicing the DGU procedure established through optical absorbance may be employed being an active film into TFTs. **b** A maximum-yield and easy division process utilizing agarose gel electrophoresis that allows the parting not just of metallic and s-CNTs but also

of individual chirality. **c** The particular position of classified CNTs including a great CNT density with an ion-exchange chemistry method. The outcomes of electrically correlated tools are greater than 90% to a high density of CNT transistors into a single disk. The channels into some tools are electrically small with metallic or bunches CNTs [249]

maintaining in look the potential utilization of a natural polymer. Besides the benefits of excellent bio-adaptability, bio-degradability and excellent mechanical characteristics, it is tried here to build a high-performance liquid chromatography-mass spectroscopy (HPLC–MS/MS) approach to trace the in vivo degeneration of permeable zein framework.

Transparent electrodes are of primary interest within electronics and energy machinery. Currently, TCOs are essentially n-type conductors controlling the business and have limited technological progress. Recently, Rajanna et al. [122] developed a unique, balanced perspective of a p-type stretchable TCF based upon SWCNTs mixed by PEDOT:PSS, molybdenum oxide (MoO_3) and SWCNT fibers. While an arrangement of SWCNTs– MoO_3 –PEDOT:PSS/SWCNT fibers, it obtained a maximum equal sheet

resistance about $17 \Omega/\text{sq}$ including transmittance around 90% on 550 nm and a high degree of versatility.

Comparison between CNT and other conducting films

TCs are brittle and manage to crack down owing to weakness. The most usually utilized TCO is ITO because of its excellent electrical characteristics and efficiency of incorporation. Though these transparent sheets usually are delicate and, like difficulties as structure mismatch and stress–strain restraints guide to limitations within feasible applications toward TCFs. ITO has been conferred to deteriorate by the time when directed to mechanical strains. New advances in



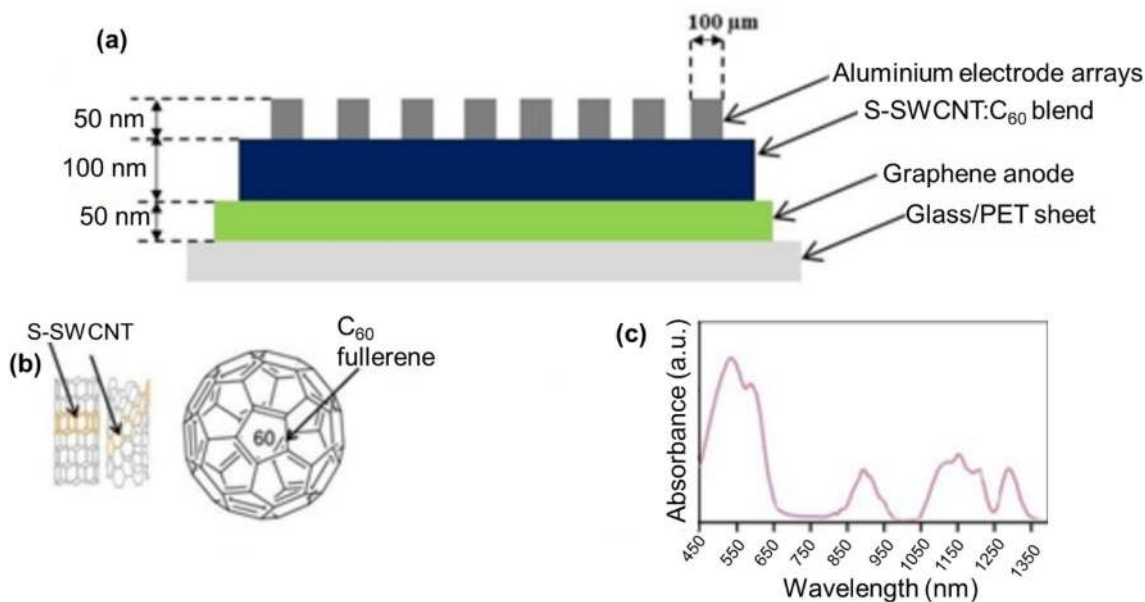


Fig. 19 System performance of the bio-organic interface: **a** Diagram illustration of nano photodiode cell **(b)** Chemical compositions of S-SWCNT and C₆₀ fullerene **(c)** Spectral effect of S-SWCNT: C₆₀ mixture suspension [253]

price are also pushing several to see to CNT films as a possible option.

CNTs have drawn significant consideration because of their substances characteristics, with a tremendous elastic modulus ($\sim 1\text{--}2$ TPa), a tremendous tensile strength ($\sim 13\text{--}53$ GPa), and an excellent conductivity (metallic tubes may provide an electric current density of 4×10^9 A/cm², that is ~ 1000 times higher compared to different elements, for example, copper) [44]. CNT transparent sheets have been employed as translucent electrodes into TCFs because of these excellent electronic characteristics.

CNTs may also be utilized as well as TCOs within thin-film photovoltaic designs. Two TCOs that are usually practiced are ZnO/Al and In₂O₃/Sn ITO. PV projects formed by these TCOs accomplished energy-alteration effectiveness of 19.5% into CuIn_{1-x}Ga₁Se₂-dependent solar cells and 16.5% under Cadmium telluride (CdTe)-dependent solar cells. These photovoltaic projects had much greater capabilities than the designs composed of CNT thin sheets. Rakesh et al. [262] reported an effectiveness about 8%, through an open circuit voltage (V_{oc}) of 0.676 V, a short circuit flux (J_{sc}) of 23.9 mA/cm², and a block factor of 45.48%. Though, CNT transparent sheets exhibit several advantages on another transparent electrode under the IR spectrum. CNT thin films were described to become a transmission of above 90% during the scale (400 nm—22 μm). It clears the path toward modern applicability, intimating that CNT thin films may be utilized as heat dissipaters into solar cells because of this great transmission [263].

As affirmed earlier, nanotube chirality is essential in assisting conclude its potential support to these tools. Before mass generation may happen, more investigation is required while investigating the importance of tube diameter and chirality for TCFs into photovoltaic uses. It is assumed that the electrical performance of the SWNT thin sheets will improve by an improvement into CNT length and pureness. The CNT films are produced utilizing randomly located bunches of CNTs. Placing these tubes would also enhance electrical activity, as this would reduce distributing damages and enhance the connection among the nanotubes.

Conclusion, challenges, and future prospect

Here, we discussed a broad survey of the history, overview, characteristics, incorporation, designing, and potential implementation of CNT-TCFs. CNT-TCFs possess exceptional characteristics, for example, high transparency, excellent electrical and elasticity, showing their great candidate as translucent probes toward optoelectronic materials. ITO has ruled the demand for TCFs for many decades and is present yet the winner of the competition for the exacting of transparent conducting substances. Nevertheless, including their prompt growth of compact electronic gadgets, modern CNT-TCFs have also developed in many advanced scenarios. When compared to ITO, the adaptability towards newer generation is much better, creating a tough competition in the areas of stretchable electronics.



The application of thin multi-ingredient films and the initiation of high-conductive SWCNT fibers have succeeded into a significant development within the TCF improvement. SWCNT fibers as such may be utilized as a substitution toward conventional metal connections owing upon their high conductivity and easy accumulation method as described. Studies and advancements of all-nanocarbon TFTs will be an example of the most active investigation areas to deliver much resilient, transparent and stretchable electronic tools. This will be probable to understand unique electronics with non-planar combined circuits, head-up exhibits and compact radio frequency description labels.

Also, to more enhance the characteristics of the CNT-based TCFs to match the specifications toward the uses, for example, the working probe of OLED screens, several dopants have been employed to manage the performance of both CNTs and CNT TCFs composite doped through another substance has been composed. Though, there are few hurdles to be overwhelmed before CNTs may be utilized during large scale production: (i) several approaches have been extended to prepare CNTs within different structures and dimensions including fast completion time, still, the maximum of the synthetic processes are energy-absorbing also subsequent refinement systems, the CNT output is not clear. (ii) A huge quantity of techniques to manufacture CNT-TCFs including required designs, still some of those techniques have been marketed owing to several disadvantages. (iii) The common important problem is large scale production of CNT-TCFs including economical price. (iv) wide dopants have been studied and their performances have been confirmed, although incorporating impacts do not remain constant for prolonged toward industrial and solar cell utilization; the humidity, along with other elements within the atmosphere, can break the patterns. (v) How to shine the exterior of TCFs and enhance the progress proportion of the ensuing tools. During the industrialization of all TCFs, this is crucial to discuss the preceding hurdles.

In general, carbon nanomaterials, for example, CNTs and graphene have been exhibiting the high potential to incorporate stretchable TFTs and transform various features of our life into the prospect. The most important responsibility on now is to manufacture resilient, stretchable and translucent electronics through practicing a high-throughput, economic, and manufacturing scale-up method, preferably than traditional semiconductor construction within the lab.

Therefore, the explanation and optimization of incorporation methods at an economical price, development of the durability of the materials comprising CNT TCFs, and answers for wide-range production are the principal points in the coming days. Despite these various hurdles, the prospect of CNT TCFs is incredibly shiny, owing to not just the novel characteristics of CNTs but besides the encouraging investigation outcomes depends upon the constant attempts

in this area. All things considered; we suppose that CNT-TCFs will grow a successful ingredient of optoelectronic tools in the coming days. Investigations on high-efficiency CNT-TCFs may encourage the growth concerning not just technical implementation but also the basic science of relevant nanostructured substances and nanomaterials. It is also of importance toward supporting the development and efficient utilization of nanoscience and nanotechnology.

Acknowledgements The authors gratefully acknowledge financial support of the National Natural Science Foundation of China (21962008, 51464028), Yunnan Province Excellent Youth Fund Project (202001AW070005), Candidate Talents Training Fund of Yunnan Province (2017PY269SQ, 2018HB007), and Yunnan Ten Thousand Talents Plan Young & Elite Talents Project (YNWR-QNBJ-2018-346).

Author contributions Original article draft is written, S.S.S.; Reviewing and editing of the manuscript, S.S.S., A.K.S., S.R, Q.B.Z., and V.K.T.; Funding accession, S.S.S., and Q.B.Z. All authors have read and approved the published form of the article.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Hosono, H., Paine, D.C., Ginley, D.: Handbook of transparent conductors 1ed. Springer, (2010)
2. Zhao, H., Geng, W., Cao, W.-W., Wen, J.-G., Wang, T., Tian, Y., Jing, L.-C., Yuan, X.-T., Zhu, Z.-R., Geng, H.-Z.: Highly stable and conductive PEDOT:PSS/GO-SWCNT bilayer transparent conductive films. *New J. Chem.* **44**(3), 780–790 (2020)
3. Xie, R., Sugime, H., Noda, S.: Dispersing and doping carbon nanotubes by poly(p-styrene-sulfonic acid) for high-performance and stable transparent conductive films. *Carbon* **164**, 150–156 (2020)
4. Mei, F., Li, R., Yuan, T.: 20-Transparent and conductive applications of tin oxide. In: Orlandi, M.O. (ed.) *Tin Oxide Materials*. pp. 579–597. Elsevier, (2020)
5. Gökçeli, G., Karatepe, N.: Improving the properties of indium tin oxide thin films by the incorporation of carbon nanotubes with solution-based techniques. *Thin Solid Films* **697**, 137844 (2020)
6. Kumar, A., Zhou, C.: The race to replace tin-doped indium oxide: which material will win? *ACS Nano* **4**(1), 11–14 (2010)
7. Singh, M., Haverinen, H.M., Dhagat, P., Jabbour, G.E.: Inkjet printing—process and its applications. *Adv. Mater.* **22**(6), 673–685 (2010)
8. Ellmer, K.: Past achievements and future challenges in the development of optically transparent electrodes. *Nat. Photon.* **6**(12), 809–817 (2012)

9. Song, J., Zeng, H.: Transparent electrodes printed with nanocrystal inks for flexible smart devices. *Angew. Chem. Int. Ed.* **54**(34), 9760–9774 (2015)
10. Omaña-Sanz, B., Toybou, D., Lesven, L., Gaucher, V., Fadel, A., Addad, A., Recourt, P., Yeghicheyan, D., Arndt, D., Celle, C., Simonato, J.-P., Vulpe, C., Charlet, L., Sobanska, S., Gilbert, B., Hofmann, A.: An electrochemical method to rapidly assess the environmental risk of silver release from nanowire transparent conductive films. *NanoImpact* **18**, 100217 (2020)
11. Hecht, D.S., Heintz, A.M., Lee, R., Hu, L., Moore, B., Cucksey, C., Risser, S.: High conductivity transparent carbon nanotube films deposited from superacid. *Nanotechnol.* **22**(7), 075201 (2011)
12. Kaskela, A., Laiho, P., Fukaya, N., Mustonen, K., Susi, T., Jiang, H., Houbenov, N., Ohno, Y., Kauppinen, E.I.: Highly individual SWCNTs for high performance thin film electronics. *Carbon* **103**, 228–234 (2016)
13. Bae, S., Kim, H., Lee, Y., Xu, X., Park, J.-S., Zheng, Y., Balakrishnan, J., Lei, T., Ri Kim, H., Song, Y.I., Kim, Y.-J., Kim, K.S., Özyilmaz, B., Ahn, J.-H., Hong, B.H., Iijima, S.: Roll-to-roll production of 30-inch graphene films for transparent electrodes. *Nat. Nanotechnol.* **5**(8), 574–578 (2010)
14. Lee, J.-Y., Connor, S.T., Cui, Y., Peumans, P.: Solution-processed metal nanowire mesh transparent electrodes. *Nano Lett.* **8**(2), 689–692 (2008)
15. Xia, Y., Sun, K., Ouyang, J.: Solution-processed metallic conducting polymer films as transparent electrode of optoelectronic devices. *Adv. Mater.* **24**(18), 2436–2440 (2012)
16. Siwal, S., Devi, N., Perla, V.K., Ghosh, S.K., Mallick, K.: Promotional role of gold in electrochemical methanol oxidation. *Catal. Struct. React* **5**(1), 1–9 (2019)
17. Feng, C., Liu, K., Wu, J.-S., Liu, L., Cheng, J.-S., Zhang, Y., Sun, Y., Li, Q., Fan, S., Jiang, K.: Flexible, stretchable, transparent conducting films made from superaligned carbon nanotubes. *Adv. Funct. Mater.* **20**(6), 885–891 (2010)
18. Zhang, J., Gao, L., Sun, J., Liu, Y., Wang, Y., Wang, J.: Incorporation of single-walled carbon nanotubes with PEDOT/PSS in DMSO for the production of transparent conducting films. *Diam. Relat. Mater.* **22**, 82–87 (2012)
19. Hecht, D.S., Thomas, D., Hu, L., Ladous, C., Lam, T., Park, Y., Irvin, G., Drzaic, P.: Carbon-nanotube film on plastic as transparent electrode for resistive touch screens. *J. Soc. Inf. Disp.* **17**(11), 941–946 (2009)
20. Wu, Z., Chen, Z., Du, X., Logan, J.M., Sippel, J., Nikolou, M., Kamaras, K., Reynolds, J.R., Tanner, D.B., Hebard, A.F., Rinzler, A.G.: Transparent, conductive carbon nanotube films. *Science* **305**(5688), 1273 (2004)
21. Hou, P.-X., Li, W.-S., Zhao, S.-Y., Li, G.-X., Shi, C., Liu, C., Cheng, H.-M.: Preparation of metallic single-wall carbon nanotubes by selective etching. *ACS Nano* **8**(7), 7156–7162 (2014)
22. Mustonen, K., Laiho, P., Kaskela, A., Susi, T., Nasibulin, A.G., Kauppinen, E.I.: Uncovering the ultimate performance of single-walled carbon nanotube films as transparent conductors. *Appl. Phys. Lett.* **107**(14), 143113 (2015)
23. Bierdel, M., Buchholz, S., Michele, V., Mleczko, L., Rudolf, R., Voetz, M., Wolf, A.: Industrial production of multiwalled carbon nanotubes. *Phys. Status Sol (b)* **244**(11), 3939–3943 (2007)
24. Kumanek, B., Wasiak, T., Stando, G., Stando, P., Łukowiec, D., Janas, D.: Simple method to improve electrical conductivity of films made from single-walled carbon nanotubes. *Nanomaterials* **9**(8) (2019)
25. Li, E.Y., Marzari, N.: Improving the electrical conductivity of carbon nanotube networks: a first-principles study. *ACS Nano* **5**(12), 9726–9736 (2011)
26. Oluwalowo, A., Nguyen, N., Zhang, S., Park, J.G., Liang, R.: Electrical and thermal conductivity improvement of carbon nanotube and silver composites. *Carbon* **146**, 224–231 (2019)
27. Neibolts, N., Platnieks, O., Gaidukovs, S., Barkane, A., Thakur, V.K., Filipova, I., Mihai, G., Zelca, Z., Yamaguchi, K., Enachescu, M.: Needle-free electrospinning of nanofibrillated cellulose and graphene nanoplatelets based sustainable poly (butylene succinate) nanofibers. *Mater. Today Chem.* **17**, 100301 (2020)
28. Ates, B., Koytepe, S., Ulu, A., Gurses, C., Thakur, V.K.: Chemistry, structures, and advanced applications of nanocomposites from biorenewable resources. *Chem. Rev.* **120**(17), 9304–9362 (2020)
29. Stadler, A.: Transparent conducting oxides—an up-to-date overview. *Materials (Basel)* **5**(4), 661–683 (2012)
30. Minami, T.: Transparent conducting oxide semiconductors for transparent electrodes. *Semicond. Sci. Technol.* **20**(4), S35–S44 (2005)
31. Minami, T.: Present status of transparent conducting oxide thin-film development for indium-tin-oxide (ITO) substitutes. *Thin Solid Films* **516**(17), 5822–5828 (2008)
32. Bühler, G., Thölmann, D., Feldmann, C.: One-pot synthesis of highly conductive indium tin oxide nanocrystals. *Adv. Mater.* **19**(17), 2224–2227 (2007)
33. Menampambath, M.M., Muhammed Ajmal, C., Kim, K.H., Yang, D., Roh, J., Park, H.C., Kwak, C., Choi, J.-Y., Baik, S.: Silver nanowires decorated with silver nanoparticles for low-haze flexible transparent conductive films. *Sci. Rep.* **5**(1), 16371 (2015)
34. Sugawara, K., Hayashi, Y., Fukushima, J., Takizawa, H.: Facile synthesis of silver-nanobeadwire transparent conductive film by organic-precursor paint reduction. *Cryst. Res. Technol.* **50**(4), 319–330 (2015)
35. José Andrés, L., Fe Menéndez, M., Gómez, D., Luisa Martínez, A., Bristow, N., Paul Kettle, J., Menéndez, A., Ruiz, B.: Rapid synthesis of ultra-long silver nanowires for tailor-made transparent conductive electrodes: proof of concept in organic solar cells. *Nanotechnol.* **26**(26), 265201 (2015)
36. Jiang, Y., Xi, J., Wu, Z., Dong, H., Zhao, Z., Jiao, B., Hou, X.: Highly transparent, conductive, flexible resin films embedded with silver nanowires. *Langmuir* **31**(17), 4950–4957 (2015)
37. Jia, Y., Chen, C., Jia, D., Li, S., Ji, S., Ye, C.: Silver nanowire transparent conductive films with high uniformity fabricated via a dynamic heating method. *ACS Appl. Mater. Interfaces* **8**(15), 9865–9871 (2016)
38. Tian, J.-L., Zhang, H.-Y., Wang, H.-J.: Preparation and properties of silver nanowire-based transparent conductive composite films. *J. Electronic Mater.* **45**(6), 3040–3045 (2016)
39. Hunger, C., Rao, K.D.M., Gupta, R., Singh, C.R., Kulkarni, G.U., Thelakkat, M.: Transparent metal network with low haze and high figure of merit applied to front and back electrodes in semi-transparent ito-free polymer solar cells. *Energy Technol.* **3**(6), 638–645 (2015)
40. Marzbanrad, E., Rivers, G., Peng, P., Zhao, B., Zhou, N.Y.: How morphology and surface crystal texture affect thermal stability of a metallic nanoparticle: the case of silver nanobelts and pentagonal silver nanowires. *Phs. Chem. Chem. Phys.* **17**(1), 315–324 (2015)
41. Song, T.-B., Chen, Y., Chung, C.-H., Yang, Y., Bob, B., Duan, H.-S., Li, G., Tu, K.-N., Huang, Y., Yang, Y.: Nanoscale joule heating and electromigration enhanced ripening of silver nanowire contacts. *ACS Nano* **8**(3), 2804–2811 (2014)
42. Park, S., Vosguerichian, M., Bao, Z.: A review of fabrication and applications of carbon nanotube film-based flexible electronics. *Nanoscale* **5**(5), 1727–1752 (2013)



43. Yu, M.-F., Lourie, O., Dyer, M.J., Moloni, K., Kelly, T.F., Ruoff, R.S.: Strength and breaking mechanism of multiwalled carbon nanotubes under tensile load. *Science* **287**(5453), 637 (2000)
44. Hong, S., Myung, S.: A flexible approach to mobility. *Nat. Nanotechnol.* **2**(4), 207–208 (2007)
45. Pop, E., Mann, D., Wang, Q., Goodson, K., Dai, H.: Thermal conductance of an individual single-wall carbon nanotube above room temperature. *Nano Lett.* **6**(1), 96–100 (2006)
46. Kataura, H., Kumazawa, Y., Maniwa, Y., Umez, I., Suzuki, S., Ohtsuka, Y., Achiba, Y.: Optical properties of single-wall carbon nanotubes. *Synth. Met.* **103**(1), 2555–2558 (1999)
47. Iijima, S.: Helical microtubules of graphitic carbon. *Nature* **354**(6348), 56–58 (1991)
48. Iijima, S., Ichihashi, T.: Single-shell carbon nanotubes of 1-nm diameter. *Nature* **363**(6430), 603–605 (1993)
49. Maiti, U.N., Lee, W.J., Lee, J.M., Oh, Y., Kim, J.Y., Kim, J.E., Shim, J., Han, T.H., Kim, S.O.: 25th anniversary article: chemically modified/doped carbon nanotubes & graphene for optimized nanostructures & nanodevices. *Adv. Mater.* **26**(1), 40–67 (2014)
50. Yang, F., Wang, X., Zhang, D., Yang, J., Luo, D., Xu, Z., Wei, J., Wang, J.-Q., Xu, Z., Peng, F., Li, X., Li, R., Li, Y., Li, M., Bai, X., Ding, F., Li, Y.: Chirality-specific growth of single-walled carbon nanotubes on solid alloy catalysts. *Nature* **510**(7506), 522–524 (2014)
51. Wang, B.-W., Jiang, S., Zhu, Q.-B., Sun, Y., Luan, J., Hou, P.-X., Qiu, S., Li, Q.-W., Liu, C., Sun, D.-M., Cheng, H.-M.: Continuous fabrication of meter-scale single-wall carbon nanotube films and their use in flexible and transparent integrated circuits. *Adv. Mater.* **30**(32), 1802057 (2018)
52. Goh, P.S., Ismail, A.F., Ng, B.C.: Directional alignment of carbon nanotubes in polymer matrices: contemporary approaches and future advances. *Compos. Part A: Appl. Sci. Manufact.* **56**, 103–126 (2014)
53. Park, J.H., Hwang, G.-T., Kim, S., Seo, J., Park, H.-J., Yu, K., Kim, T.-S., Lee, K.J.: Flash-induced self-limited plasmonic welding of silver nanowire network for transparent flexible energy harvester. *Adv. Mater.* **29**(5), 1603473 (2017)
54. Sau, T.K., Rogach, A.L., Jäckel, F., Klar, T.A., Feldmann, J.: Properties and applications of colloidal nonspherical noble metal nanoparticles. *Adv. Mater.* **22**(16), 1805–1825 (2010)
55. Choi, D., Lee, M., Kim, H., Chu, W.-S., Chun, D.-M., Ahn, S.-H., Lee, C.S.: Fabrication of transparent conductive tri-composite film for electrochromic application. *Appl. Surf. Sci.* **425**, 1006–1013 (2017)
56. Liu, H., Avrutin, V., Izyumskaya, N., Özgür, Ü., Morkoç, H.: Transparent conducting oxides for electrode applications in light emitting and absorbing devices. *Superlattice. Microst.* **48**(5), 458–484 (2010)
57. Viespe, C., Nicolae, I., Sima, C., Grigoriu, C., Medianu, R.: ITO thin films deposited by advanced pulsed laser deposition. *Thin Solid Films* **515**(24), 8771–8775 (2007)
58. Layani, M., Kamyshny, A., Magdassi, S.: Transparent conductors composed of nanomaterials. *Nanoscale* **6**(11), 5581–5591 (2014)
59. De, S., King, P.J., Lyons, P.E., Khan, U., Coleman, J.N.: Size Effects and the problem with percolation in nanostructured transparent conductors. *ACS Nano* **4**(12), 7064–7072 (2010)
60. Chamoli, P., Srivastava, T., Tyagi, A., Raina, K.K., Kar, K.K.: Urea and cow urine-based green approach to fabricate graphene-based transparent conductive films with high conductivity and transparency. *Mater. Chem. Phys.* **242**, 122465 (2020)
61. Cheng, T., Zhang, Y., Lai, W.-Y., Huang, W.: Stretchable thin-film electrodes for flexible electronics with high deformability and stretchability. *Adv. Mater.* **27**(22), 3349–3376 (2015)
62. Feng, X.-M., Li, R.-M., Ma, Y.-W., Chen, R.-F., Shi, N.-E., Fan, Q.-L., Huang, W.: One-step electrochemical synthesis of graphene/polyaniline composite film and its applications. *Adv. Funct. Mater.* **21**(15), 2989–2996 (2011)
63. Hecht, D.S., Hu, L., Irvin, G.: Emerging transparent electrodes based on thin films of carbon nanotubes, graphene, and metallic nanostructures. *Adv. Mater.* **23**(13), 1482–1513 (2011)
64. Du, J., Pei, S., Ma, L., Cheng, H.-M.: 25th anniversary article: carbon nanotube- and graphene-based transparent conductive films for optoelectronic devices. *Adv. Mater.* **26**(13), 1958–1991 (2014)
65. Li, D., Lai, W.-Y., Zhang, Y.-Z., Huang, W.: Printable transparent conductive films for flexible electronics. *Adv. Mater.* **30**(10), 1704738 (2018)
66. Rowell, M.W., McGehee, M.D.: Transparent electrode requirements for thin film solar cell modules. *Energy Environ. Sci.* **4**(1), 131–134 (2011)
67. Thejokalyani, N., Dhoble, S.J.: Novel approaches for energy efficient solid state lighting by RGB organic light emitting diodes—a review. *Renew. Sustain. Energy Rev.* **32**, 448–467 (2014)
68. Jariwala, D., Sangwan, V.K., Lauhon, L.J., Marks, T.J., Hersam, M.C.: Carbon nanomaterials for electronics, optoelectronics, photovoltaics, and sensing. *Chem. Soc. Rev.* **42**(7), 2824–2860 (2013)
69. Ozel, T., Abdula, D., Hwang, E., Shim, M.: Nonuniform compressive strain in horizontally aligned single-walled carbon nanotubes grown on single crystal quartz. *ACS Nano* **3**(8), 2217–2224 (2009)
70. Caudal, N., Saitta, A.M., Lazzeri, M., Mauri, F.: Kohn anomalies and nonadiabaticity in doped carbon nanotubes. *Phys. Rev. B* **75**(11), 115423 (2007)
71. Wang, C., Cao, Q., Ozel, T., Gaur, A., Rogers, J.A., Shim, M.: Electronically selective chemical functionalization of carbon nanotubes: correlation between raman spectral and electrical responses. *J. Am. Chem. Soc.* **127**(32), 11460–11468 (2005)
72. Han, J.T., Kim, J.S., Jeong, H.D., Jeong, H.J., Jeong, S.Y., Lee, G.-W.: Modulating conductivity, environmental stability of transparent conducting nanotube films on flexible substrates by interfacial engineering. *ACS Nano* **4**(8), 4551–4558 (2010)
73. Schindler, A.: ITO replacements: carbon nanotubes. In: Chen, J., Cranton, W., Fihn, M. (eds.) *Handbook of visual display technology*, pp. 1235–1255. Springer International Publishing, Cham (2016)
74. Warheit, D.B., Sayes, C.M., Reed, K.L., Swain, K.A.: Health effects related to nanoparticle exposures: Environmental, health and safety considerations for assessing hazards and risks. *Pharmacol. Therapeut.* **120**(1), 35–42 (2008)
75. Nowack, B., David, R.M., Fissan, H., Morris, H., Shatkin, J.A., Stintz, M., Zepp, R., Brouwer, D.: Potential release scenarios for carbon nanotubes used in composites. *Environ. Int.* **59**, 1–11 (2013)
76. Petersen, E.J., Zhang, L., Mattison, N.T., O’Carroll, D.M., Whelton, A.J., Uddin, N., Nguyen, T., Huang, Q., Henry, T.B., Holbrook, R.D., Chen, K.L.: Potential release pathways, environmental fate, and ecological risks of carbon nanotubes. *Environ. Sci. Technol.* **45**(23), 9837–9856 (2011)
77. Deline, A.R., Frank, B.P., Smith, C.L., Sigmon, L.R., Wallace, A.N., Gallagher, M.J., Goodwin, D.G., Durkin, D.P., Fairbrother, D.H.: Influence of oxygen-containing functional groups on the environmental properties, transformations, and toxicity of carbon nanotubes. *Chem. Rev.* **120**(20), 11651–11697 (2020)
78. Ma, G., Ren, Y., Guo, J., Xiao, T., Li, F., Cheng, H., Zhou, Z., Liao, K.: How long can single-walled carbon nanotube ropes last under static or dynamic fatigue? *Appl. Phys. Lett.* **92**(8), 083105 (2008)



79. Yakobson, B.I., Brabec, C.J., Bernholc, J.: Nanomechanics of carbon tubes: instabilities beyond linear response. *Phys. Rev. Lett.* **76**(14), 2511–2514 (1996)
80. Attia, N.F., Mohamed, G.G., Ismail, M.M., Abdou, T.T.: Influence of organic modifier structures of 2D clay layers on thermal stability, flammability and mechanical properties of their rubber nanocomposites. *J. Nanostruct. Chem.* **10**(2), 161–168 (2020)
81. Cumings, J., Zettl, A.: Low-friction nanoscale linear bearing realized from multiwall carbon nanotubes. *Science* **289**(5479), 602 (2000)
82. Cai, L., Li, J., Luan, P., Dong, H., Zhao, D., Zhang, Q., Zhang, X., Tu, M., Zeng, Q., Zhou, W., Xie, S.: Highly transparent and conductive stretchable conductors based on hierarchical reticulate single-walled carbon nanotube architecture. *Adv. Funct. Mater.* **22**(24), 5238–5244 (2012)
83. Chen, Z., Cotterell, B., Wang, W., Guenther, E., Chua, S.-J.: A mechanical assessment of flexible optoelectronic devices. *Thin Solid Films* **394**(1), 201–205 (2001)
84. Shim, B.S., Zhu, J., Jan, E., Critchley, K., Kotov, N.A.: Transparent conductors from layer-by-layer assembled SWNT films: importance of mechanical properties and a new figure of merit. *ACS Nano* **4**(7), 3725–3734 (2010)
85. Zhou, C., Kumar, S., Doyle, C.D., Tour, J.M.: Functionalized single wall carbon nanotubes treated with pyrrole for electrochemical supercapacitor membranes. *Chem. Mater.* **17**(8), 1997–2002 (2005)
86. D'yachkov, P.N., Hermann, H.: Electronic structure and interband transitions of semiconducting carbon nanotubes. *J. Appl. Phys.* **95**(1), 399–401 (2003)
87. Wilder, J.W.G., Venema, L.C., Rinzler, A.G., Smalley, R.E., Dekker, C.: Electronic structure of atomically resolved carbon nanotubes. *Nature* **391**(6662), 59–62 (1998)
88. Kane, C.L., Mele, E.J.: Size, shape, and low energy electronic structure of carbon nanotubes. *Phys. Rev. Lett.* **78**(10), 1932–1935 (1997)
89. Molani, F.: The effect of C, Si, N, and P impurities on structural and electronic properties of armchair boron nanotube. *J. Nanostruct. Chem.* **7**(3), 243–248 (2017)
90. Léonard, F., Tersoff, J.: Role of fermi-level pinning in nanotube schottky diodes. *Phys. Rev. Lett.* **84**(20), 4693–4696 (2000)
91. Ham, H.T., Choi, Y.S., Jeong, N., Chung, I.J.: Singlewall carbon nanotubes covered with polypyrrole nanoparticles by the miniemulsion polymerization. *Polymer* **46**(17), 6308–6315 (2005)
92. Su, W.S., Leung, T.C., Li, B., Chan, C.T.: Work function of small radius carbon nanotubes and their bundles. *Appl. Phys. Lett.* **90**(16), 163103 (2007)
93. Zhao, J., Han, J., Lu, J.P.: Work functions of pristine and alkali-metal intercalated carbon nanotubes and bundles. *Phys. Rev. B* **65**(19), 193401 (2002)
94. Dresselhaus, M.S., Dresselhaus, G.: Intercalation compounds of graphite. *Adv. Phys.* **51**(1), 1–186 (2002)
95. Hu, L., Hecht, D.S., Grüner, G.: Infrared transparent carbon nanotube thin films. *Appl. Phys. Lett.* **94**(8), 081103 (2009)
96. Han, J., Yuan, S., Liu, L., Qiu, X., Gong, H., Yang, X., Li, C., Hao, Y., Cao, B.: Fully indium-free flexible Ag nanowires/ZnO: F composite transparent conductive electrodes with high haze. *J. Mater. Chem. A* **3**(10), 5375–5384 (2015)
97. Martin, C.A., Sandler, J.K.W., Shaffer, M.S.P., Schwarz, M.K., Bauhofer, W., Schulte, K., Windle, A.H.: Formation of percolating networks in multi-wall carbon-nanotube-epoxy composites. *Compos. Sci. Technol.* **64**(15), 2309–2316 (2004)
98. Huang, J., Mao, C., Zhu, Y., Jiang, W., Yang, X.: Control of carbon nanotubes at the interface of a co-continuous immiscible polymer blend to fabricate conductive composites with ultralow percolation thresholds. *Carbon* **73**, 267–274 (2014)
99. Harris, J.M., Huh, J.Y., Semler, M.R., Ihle, T., Stafford, C.M., Hudson, S.D., Fagan, J.A., Hobbie, E.K.: Elasticity and rigidity percolation in flexible carbon nanotube films on PDMS substrates. *Soft Matter* **9**(48), 11568–11575 (2013)
100. Tian, X., Moser, M.L., Pekker, A., Sarkar, S., Ramirez, J., Bekyarova, E., Itkis, M.E., Haddon, R.C.: Effect of atomic interconnects on percolation in single-walled carbon nanotube thin film networks. *Nano Lett.* **14**(7), 3930–3937 (2014)
101. Geng, H.-Z., Kim, K.K., Lee, K.Y.U., Kim, G.Y., Choi, H.K., Lee, D.S., An, K.H., Lee, Y.H., Chang, Y., Lee, Y.S., Kim, B., Lee, Y.J.: Dependence of material quality on performance of flexible transparent conducting films with single-walled carbon nanotubes. *NANO* **02**(03), 157–167 (2007)
102. Sarkar, S.K., Jha, A., Chattopadhyay, K.K.: Thionyl chloride assisted functionalization of amorphous carbon nanotubes: a better field emitter and stable nanofluid with better thermal conductivity. *Mater. Res. Bull.* **66**, 1–8 (2015)
103. Chen, J., Lekawa-Raus, A., Trevarthen, J., Gizewski, T., Lukawski, D., Hazra, K., Rahatekar, S.S., Koziol, K.K.K.: Carbon nanotube films spun from a gas phase reactor for manufacturing carbon nanotube film/carbon fibre epoxy hybrid composites for electrical applications. *Carbon* **158**, 282–290 (2020)
104. Goak, J.C., Lee, S.H., Lee, N.: Effect of purification on the electrical properties of transparent conductive films fabricated from single-walled carbon nanotubes. *Diam. Relat. Mater.* **106**, 107815 (2020)
105. Saran, N., Parikh, K., Suh, D.-S., Muñoz, E., Kolla, H., Manohar, S.K.: Fabrication and characterization of thin films of single-walled carbon nanotube bundles on flexible plastic substrates. *J. Am. Chem. Soc.* **126**(14), 4462–4463 (2004)
106. Ma, W., Song, L., Yang, R., Zhang, T., Zhao, Y., Sun, L., Ren, Y., Liu, D., Liu, L., Shen, J., Zhang, Z., Xiang, Y., Zhou, W., Xie, S.: Directly synthesized strong, highly conducting, transparent single-walled carbon nanotube films. *Nano Lett.* **7**(8), 2307–2311 (2007)
107. Nasibulin, A.G., Kaskela, A., Mustonen, K., Anisimov, A.S., Ruiz, V., Kivistö, S., Rackauskas, S., Timmermans, M.Y., Pudas, M., Aitchison, B., Kauppinen, M., Brown, D.P., Okhotnikov, O.G., Kauppinen, E.I.: Multifunctional free-standing single-walled carbon nanotube films. *ACS Nano* **5**(4), 3214–3221 (2011)
108. Liu, X., Han, S., Zhou, C.: Novel nanotube-on-insulator (noi) approach toward single-walled carbon nanotube devices. *Nano Lett.* **6**(1), 34–39 (2006)
109. Reynaud, O., Nasibulin, A.G., Anisimov, A.S., Anoshkin, I.V., Jiang, H., Kauppinen, E.I.: Aerosol feeding of catalyst precursor for CNT synthesis and highly conductive and transparent film fabrication. *Chem. Eng. J.* **255**, 134–140 (2014)
110. Kaskela, A., Nasibulin, A.G., Timmermans, M.Y., Aitchison, B., Papadimitratos, A., Tian, Y., Zhu, Z., Jiang, H., Brown, D.P., Zakhidov, A., Kauppinen, E.I.: Aerosol-synthesized SWCNT networks with tunable conductivity and transparency by a dry transfer technique. *Nano Lett.* **10**(11), 4349–4355 (2010)
111. Cheng, H.M., Li, F., Su, G., Pan, H.Y., He, L.L., Sun, X., Dresselhaus, M.S.: Large-scale and low-cost synthesis of single-walled carbon nanotubes by the catalytic pyrolysis of hydrocarbons. *Appl. Phys. Lett.* **72**(25), 3282–3284 (1998)
112. Kato, H., Nakamura, A., Horie, M.: Behavior of surfactants in aqueous dispersions of single-walled carbon nanotubes. *RSC Adv.* **4**(5), 2129–2136 (2014)
113. Xie, X.-L., Mai, Y.-W., Zhou, X.-P.: Dispersion and alignment of carbon nanotubes in polymer matrix: a review. *Mater. Sci. Eng. R: Rep.* **49**(4), 89–112 (2005)
114. Nish, A., Hwang, J.-Y., Doig, J., Nicholas, R.J.: Highly selective dispersion of single-walled carbon nanotubes using aromatic polymers. *Nat. Nanotechnol.* **2**(10), 640–646 (2007)



115. Kim, S.W., Kim, T., Kim, Y.S., Choi, H.S., Lim, H.J., Yang, S.J., Park, C.R.: Surface modifications for the effective dispersion of carbon nanotubes in solvents and polymers. *Carbon* **50**(1), 3–33 (2012)
116. Lee, H.W., Yoon, Y., Park, S., Oh, J.H., Hong, S., Liyanage, L.S., Wang, H., Morishita, S., Patil, N., Park, Y.J., Park, J.J., Spakowitz, A., Galli, G., Gygi, F., Wong, P.H.S., Tok, J.B.H., Kim, J.M., Bao, Z.: Selective dispersion of high purity semi-conducting single-walled carbon nanotubes with regioregular poly(3-alkylthiophene)s. *Nat. Commun.* **2**(1), 541 (2011)
117. Samanta, S.K., Fritsch, M., Scherf, U., Gomulya, W., Bisri, S.Z., Loi, M.A.: Conjugated polymer-assisted dispersion of single-wall carbon nanotubes: the power of polymer wrapping. *Acc. Chem. Res.* **47**(8), 2446–2456 (2014)
118. Rösner, B., Guldi, D.M., Chen, J., Minett, A.I., Fink, R.H.: Dispersion and characterization of arc discharge single-walled carbon nanotubes—towards conducting transparent films. *Nanoscale* **6**(7), 3695–3703 (2014)
119. Jo, J.W., Jung, J.W., Lee, J.U., Jo, W.H.: Fabrication of highly conductive and transparent thin films from single-walled carbon nanotubes using a new non-ionic surfactant via spin coating. *ACS Nano* **4**(9), 5382–5388 (2010)
120. Kim, Y., Minami, N., Zhu, W., Kazaoui, S., Azumi, R., Matsu-moto, M.: Langmuir–blodgett films of single-wall carbon nanotubes: layer-by-layer deposition and in-plane orientation of tubes. *Jpn J Appl Phys* **42**(Part 1, No. 12), 7629–7634 (2003)
121. Tenent, R.C., Barnes, T.M., Bergeson, J.D., Ferguson, A.J., To, B., Gedvilas, L.M., Heben, M.J., Blackburn, J.L.: Ultrasoother, large-area, high-uniformity, conductive transparent single-walled-carbon-nanotube films for photovoltaics produced by ultrasonic spraying. *Adv. Mater.* **21**(31), 3210–3216 (2009)
122. Rajanna, P.M., Meddeb, H., Sergeev, O., Tsapenko, A.P., Bereznev, S., Vehse, M., Volobujeva, O., Danilson, M., Lund, P.D., Nasibulin, A.G.: Rational design of highly efficient flexible and transparent p-type composite electrode based on single-walled carbon nanotubes. *Nano Energy* **67**, 104183 (2020)
123. Dastgerdi, Z.H., Meshkat, S.S., Esrafil, M.D.: Enhanced adsorptive removal of Indigo carmine dye performance by functionalized carbon nanotubes based adsorbents from aqueous solution: equilibrium, kinetic, and DFT study. *J. Nanostruct. Chem.* **9**(4), 323–334 (2019)
124. Shimoni, A., Azoubel, S., Magdassi, S.: Inkjet printing of flexible high-performance carbon nanotube transparent conductive films by “coffee ring effect.” *Nanoscale* **6**(19), 11084–11089 (2014)
125. Jiang, S., Hou, P.-X., Liu, C., Cheng, H.-M.: High-performance single-wall carbon nanotube transparent conductive films. *J. Mater. Sci. Technol.* **35**(11), 2447–2462 (2019)
126. Sirringhaus, H., Kawase, T., Friend, R.H., Shimoda, T., Inbasekaran, M., Wu, W., Woo, E.P.: High-resolution inkjet printing of all-polymer transistor circuits. *Science* **290**(5499), 2123 (2000)
127. Sirringhaus, H.: Device physics of solution-processed organic field-effect transistors. *Adv. Mater.* **17**(20), 2411–2425 (2005)
128. Yan, H., Chen, Z., Zheng, Y., Newman, C., Quinn, J.R., Dötz, F., Kastler, M., Facchetti, A.: A high-mobility electron-transporting polymer for printed transistors. *Nature* **457**(7230), 679–686 (2009)
129. Kordás, K., Mustonen, T., Tóth, G., Jantunen, H., Lajunen, M., Soldano, C., Talapatra, S., Kar, S., Vajtai, R., Ajayan, P.M.: Inkjet printing of electrically conductive patterns of carbon nanotubes. *Small* **2**(8–9), 1021–1025 (2006)
130. Okimoto, H., Takenobu, T., Yanagi, K., Miyata, Y., Shimotani, H., Kataura, H., Iwasa, Y.: Tunable carbon nanotube thin-film transistors produced exclusively via inkjet printing. *Adv. Mater.* **22**(36), 3981–3986 (2010)
131. Tortorich, R.P., Song, E., Choi, J.-W.: Inkjet-printed carbon nanotube electrodes with low sheet resistance for electrochemical sensor applications. *J Electrochem. Soc.* **161**(2), B3044–B3048 (2013)
132. Bennett, R.D., Hart, A.J., Miller, A.C., Hammond, P.T., Irvine, D.J., Cohen, R.E.: Creating patterned carbon nanotube catalysts through the microcontact printing of block copolymer micellar thin films. *Langmuir* **22**(20), 8273–8276 (2006)
133. Dimitrov, A.S., Nagayama, K.: Steady-state unidirectional convective assembling of fine particles into two-dimensional arrays. *Chem. Phys. Lett.* **243**(5), 462–468 (1995)
134. Somani, P.R., Dionigi, C., Murgia, M., Palles, D., Nozar, P., Ruani, G.: Solid-state dye PV cells using inverse opal TiO₂ films. *Sol. Energy Mater. Sol. Cells* **87**(1), 513–519 (2005)
135. Goodwin, J.W., Hearn, J., Ho, C.C., Ottewill, R.H.: Studies on the preparation and characterisation of monodisperse polystyrene latices. *Coll. Polym. Sci.* **252**(6), 464–471 (1974)
136. Xia, Y., Gates, B., Yin, Y., Lu, Y.: Monodispersed colloidal spheres: old materials with new applications. *Adv. Mater.* **12**(10), 693–713 (2000)
137. Radtchenko, I.L., Sukhorukov, G.B., Gaponik, N., Kornowski, A., Rogach, A.L., Möhwald, H.: Core-shell structures formed by the solvent-controlled precipitation of luminescent CdTe nanocrystals on latex spheres. *Adv. Mater.* **13**(22), 1684–1687 (2001)
138. Dionigi, C., Stoliar, P., Porzio, W., Destri, S., Cavallini, M., Bilotti, I., Brillante, A., Biscarini, F.: Field effect transistors with organic semiconductor layers assembled from aqueous colloidal nanocomposites. *Langmuir* **23**(4), 2030–2036 (2007)
139. Dionigi, C., Stoliar, P., Ruani, G., Quiroga, S.D., Facchini, M., Biscarini, F.: Carbon nanotube networks patterned from aqueous solutions of latex bead carriers. *J. Mater. Chem.* **17**(35), 3681–3686 (2007)
140. Correa-Duarte, M.A., Kosiorek, A., Kandulski, W., Giersig, M., Liz-Marzán, L.M.: Layer-by-layer assembly of multiwall carbon nanotubes on spherical colloids. *Chem. Mater.* **17**(12), 3268–3272 (2005)
141. Li, Y., Huang, X.J., Heo, S.H., Li, C.C., Choi, Y.K., Cai, W.P., Cho, S.O.: Superhydrophobic bionic surfaces with hierarchical microsphere/SWCNT composite arrays. *Langmuir* **23**(4), 2169–2174 (2007)
142. Bhakta, A.K., Kumari, S., Hussain, S., Detriche, S., Delhalle, J., Mekhalif, Z.: Differently substituted aniline functionalized MWCNTs to anchor oxides of Bi and Ni nanoparticles. *J. Nanostruct. Chem.* **9**(4), 299–314 (2019)
143. Han, K.N., Li, C.A., Ngoc Bui, M.-P., Seong, G.H.: Patterning of single-walled carbon nanotube films on flexible. *Trans Plast Substrat Langmuir* **26**(1), 598–602 (2010)
144. Iakoubovskii, K.: Techniques of aligning carbon nanotubes. *Cent. Eur. J. Phys.* **7**(4), 645–653 (2009)
145. Arnold, M.S., Green, A.A., Hulvat, J.F., Stupp, S.I., Hersam, M.C.: Sorting carbon nanotubes by electronic structure using density differentiation. *Nat. Nanotechnol.* **1**(1), 60–65 (2006)
146. Gao, J., Wang, W.-Y., Chen, L.-T., Cui, L.-J., Hu, X.-Y., Geng, H.-Z.: Optimizing processes of dispersant concentration and post-treatments for fabricating single-walled carbon nanotube transparent conducting films. *Appl. Surf. Sci.* **277**, 128–133 (2013)
147. Thostenson, E.T., Li, C., Chou, T.-W.: Nanocomposites in context. *Compos. Sci. Technol.* **65**(3), 491–516 (2005)
148. Barnes, T.M., Blackburn, J.L., van de Lagemaat, J., Coutts, T.J., Heben, M.J.: Reversibility, dopant desorption, and tunneling in the temperature-dependent conductivity of type-separated. Conductive carbon nanotube networks. *ACS Nano* **2**(9), 1968–1976 (2008)

149. Blackburn, J.L., Barnes, T.M., Beard, M.C., Kim, Y.-H., Tenent, R.C., McDonald, T.J., To, B., Coutts, T.J., Heben, M.J.: Transparent conductive single-walled carbon nanotube networks with precisely tunable ratios of semiconducting and metallic nanotubes. *ACS Nano* **2**(6), 1266–1274 (2008)
150. Fuhrer, M.S., Nygård, J., Shih, L., Forero, M., Yoon, Y.-G., Mazzoni, M.S.C., Choi, H.J., Ihm, J., Louie, S.G., Zettl, A., McEuen, P.L.: Crossed nanotube junctions. *Science* **288**(5465), 494 (2000)
151. Parekh, B.B., Fanchini, G., Eda, G., Chhowalla, M.: Improved conductivity of transparent single-wall carbon nanotube thin films via stable postdeposition functionalization. *Appl. Phys. Lett.* **90**(12), 121913 (2007)
152. Zhou, W., Vavro, J., Nemes, N.M., Fischer, J.E., Borondics, F., Kamarás, K., Tanner, D.B.: Charge transfer and Fermi level shift in Sp^2 -doped single-walled carbon nanotubes. *Phys. Rev. B* **71**(20), 205423 (2005)
153. Dettlaff-Weglikowska, U., Skákalová, V., Graupner, R., Jhang, S.H., Kim, B.H., Lee, H.J., Ley, L., Park, Y.W., Berber, S., Tománek, D., Roth, S.: Effect of SOCl_2 treatment on electrical and mechanical properties of single-wall carbon nanotube networks. *J. Am. Chem. Soc.* **127**(14), 5125–5131 (2005)
154. Jackson, R., Domercq, B., Jain, R., Kippelen, B., Graham, S.: Stability of doped transparent carbon nanotube electrodes. *Adv. Funct. Mater.* **18**(17), 2548–2554 (2008)
155. Chandra, B., Afzali, A., Khare, N., El-Ashry, M.M., Tulevski, G.S.: Stable charge-transfer doping of transparent single-walled carbon nanotube films. *Chem. Mater.* **22**(18), 5179–5183 (2010)
156. Imazu, N., Fujigaya, T., Nakashima, N.: Fabrication of flexible transparent conductive films from long double-walled carbon nanotubes. *Sci. Technol. Adv. Mater.* **15**(2), 025005 (2014)
157. Arod, P., Shivashankar, S.A.: Single-step synthesis of carbon nanotubes/iron/iron oxide composite films through inert-ambient CVD using ferric acetylacetonate as a precursor. *RSC Adv.* **5**(73), 59463–59471 (2015)
158. Koo, H., Lee, W., Choi, Y., Sun, J., Bak, J., Noh, J., Subramanian, V., Azuma, Y., Majima, Y., Cho, G.: Scalability of carbon-nanotube-based thin film transistors for flexible electronic devices manufactured using an all roll-to-roll gravure printing system. *Sci. Rep.* **5**(1), 14459 (2015)
159. Piloto, C., Mirri, F., Bengio, E.A., Notarianni, M., Gupta, B., Shafiei, M., Pasquali, M., Motta, N.: Room temperature gas sensing properties of ultrathin carbon nanotube films by surfactant-free dip coating. *Sens. Act. B Chem.* **227**, 128–134 (2016)
160. Lee, J.-H., Kang, W.-S., Najeeb, C.K., Choi, B.-S., Choi, S.-W., Lee, H.J., Lee, S.S., Kim, J.-H.: A hydrogen gas sensor using single-walled carbon nanotube Langmuir-Blodgett films decorated with palladium nanoparticles. *Sens. Act. B Chem.* **188**, 169–175 (2013)
161. Cho, D.-Y., Eun, K., Choa, S.-H., Kim, H.-K.: Highly flexible and stretchable carbon nanotube network electrodes prepared by simple brush painting for cost-effective flexible organic solar cells. *Carbon* **66**, 530–538 (2014)
162. Kymakis, E., Stylianakis, M.M., Spyropoulos, G.D., Stratakis, E., Koudoumas, E., Fotakis, C.: Spin coated carbon nanotubes as the hole transport layer in organic photovoltaics. *Sol. Energy Mater. Sol. Cells* **96**, 298–301 (2012)
163. Ostfeld, A.E., Catheline, A., Ligsay, K., Kim, K.-C., Chen, Z., Facchetti, A., Fogden, S., Arias, A.C.: Single-walled carbon nanotube transparent conductive films fabricated by reductive dissolution and spray coating for organic photovoltaics. *Appl. Phys. Lett.* **105**(25), 253301 (2014)
164. Li, J., Zhu, Y., Wang, X., Wang, N., Zhang, J.: Light-induced vibration characteristics of free-standing carbon nanotube films fabricated by vacuum filtration. *J. Appl. Phys.* **116**(2), 023101 (2014)
165. Hellstrom, S.L., Vosgueritchian, M., Stoltenberg, R.M., Irfan, I., Hammock, M., Wang, Y.B., Jia, C., Guo, X., Gao, Y., Bao, Z.: Strong and stable doping of carbon nanotubes and graphene by MoOx for transparent electrodes. *Nano Lett.* **12**(7), 3574–3580 (2012)
166. Tokuno, T., Nogi, M., Jiu, J., Suganuma, K.: Hybrid transparent electrodes of silver nanowires and carbon nanotubes: a low-temperature solution process. *Nanosc. Res. Lett.* **7**(1), 281 (2012)
167. De, S., Lyons, P.E., Sorel, S., Doherty, E.M., King, P.J., Blau, W.J., Nirmalraj, P.N., Boland, J.J., Scardaci, V., Joimel, J., Coleman, J.N.: Transparent, flexible, and highly conductive thin films based on polymer–nanotube composites. *ACS Nano* **3**(3), 714–720 (2009)
168. Kim, S.H., Song, W., Jung, M.W., Kang, M.-A., Kim, K., Chang, S.-J., Lee, S.S., Lim, J., Hwang, J., Myung, S., An, K.-S.: Carbon nanotube and graphene hybrid thin film for transparent electrodes and field effect transistors. *Adv. Mater.* **26**(25), 4247–4252 (2014)
169. Liu, Y., Jung, E., Wang, Y., Zheng, Y., Park, E.J., Cho, S.M., Loh, K.P.: “Quasi-freestanding” graphene-on-single walled carbon nanotube electrode for applications in organic light-emitting diode. *Small* **10**(5), 944–949 (2014)
170. Kim, M., Kim, Y.C.: Single wall carbon nanotube/poly(3,4-ethylenedioxythiophene) nanocomposite film as a transparent electrode for flexible organic light-emitting diodes. *Synth. Met.* **198**, 31–35 (2014)
171. Lee, R.S., Kim, H.J., Fischer, J.E., Thess, A., Smalley, R.E.: Conductivity enhancement in single-walled carbon nanotube bundles doped with K and Br. *Nature* **388**(6639), 255–257 (1997)
172. Geng, H.-Z., Kim, K.K., So, K.P., Lee, Y.S., Chang, Y., Lee, Y.H.: Effect of acid treatment on carbon nanotube-based flexible transparent conducting films. *J. Am. Chem. Soc.* **129**(25), 7758–7759 (2007)
173. Nirmalraj, P.N., Lyons, P.E., De, S., Coleman, J.N., Boland, J.J.: Electrical connectivity in single-walled carbon nanotube networks. *Nano Lett.* **9**(11), 3890–3895 (2009)
174. De Blauwe, K., Kramberger, C., Plank, W., Kataura, H., Pichler, T.: Raman response of FeCl_3 intercalated single-wall carbon nanotubes at high doping. *Phys Stat Sol (b)* **246**(11–12), 2732–2736 (2009)
175. Kim, K.K., Bae, J.J., Park, H.K., Kim, S.M., Geng, H.-Z., Park, K.A., Shin, H.-J., Yoon, S.-M., Benayad, A., Choi, J.-Y., Lee, Y.H.: Fermi level engineering of single-walled carbon nanotubes by AuCl_3 doping. *J. Am. Chem. Soc.* **130**(38), 12757–12761 (2008)
176. Ruzicka, B., Degiorgi, L., Gaal, R., Thien-Nga, L., Bacsá, R., Salvatá, J.P., Forró, L.: Optical and dc conductivity study of potassium-doped single-walled carbon nanotube films. *Phys. Rev. B* **61**(4), R2468–R2471 (2000)
177. Kauffman, D.R., Star, A.: Chemically induced potential barriers at the carbon nanotube–metal nanoparticle interface. *Nano Lett.* **7**(7), 1863–1868 (2007)
178. Mistry, K.S., Larsen, B.A., Bergeson, J.D., Barnes, T.M., Teeter, G., Engtrakul, C., Blackburn, J.L.: n-type transparent conducting films of small molecule and polymer amine doped single-walled carbon nanotubes. *ACS Nano* **5**(5), 3714–3723 (2011)
179. Zhou, Y., Shimada, S., Saito, T., Azumi, R.: Building interconnects in carbon nanotube networks with metal halides for transparent electrodes. *Carbon* **87**, 61–69 (2015)
180. Zhou, Y., Azumi, R.: Carbon nanotube based transparent conductive films: progress, challenges, and perspectives. *Sci. Technol. Adv. Mater.* **17**(1), 493–516 (2016)



181. Koch, N., Elschner, A., Johnson, R.L., Rabe, J.P.: Energy level alignment at interfaces with pentacene: metals versus conducting polymers. *Appl. Surf. Sci.* **244**(1), 593–597 (2005)
182. Rani, A., Reddy, R., Sharma, U., Mukherjee, P., Mishra, P., Kuila, A., Sim, L.C., Saravanan, P.: A review on the progress of nanostructure materials for energy harnessing and environmental remediation. *J. Nanostruct. Chem.* **8**(3), 255–291 (2018)
183. Yang, Y., Heeger, A.J.: Polyaniline as a transparent electrode for polymer light-emitting diodes: lower operating voltage and higher efficiency. *Appl. Phys. Lett.* **64**(10), 1245–1247 (1994)
184. Islam, R.U., Taher, A., Choudhary, M., Siwal, S., Mallick, K.: Polymer immobilized Cu(I) formation and azide-alkyne cycloaddition: a one pot reaction. *Sci. Rep.* **5** (2015)
185. Kim, J.-Y., Woo, H.-Y., Baek, J.-W., Kim, T.-W., Song, E.-A., Park, S.-C., Ihm, D.-W.: Polymer-dispersed liquid crystal devices using highly conducting polymers as electrodes. *Appl. Phys. Lett.* **92**(18), 183301 (2008)
186. Becerril, H.A., Mao, J., Liu, Z., Stoltenberg, R.M., Bao, Z., Chen, Y.: Evaluation of solution-processed reduced graphene oxide films as transparent conductors. *ACS Nano* **2**(3), 463–470 (2008)
187. Siwal, S.S., Thakur, S., Zhang, Q.B., Thakur, V.K.: Electrocatalysts for electrooxidation of direct alcohol fuel cell: chemistry and applications. *Mater. Today Chem.* **14**, 100182 (2019)
188. Rydzkowski, T., Reszka, K., Szczypiński, M., Szczypiński, M.M., Koczyńska, E., Thakur, V.K.: Manufacturing and evaluation of mechanical, morphological, and thermal properties of reduced graphene oxide-reinforced expanded polystyrene (EPS) nanocomposites. *Adv. Polym. Technol.* **2020**, 3053471 (2020)
189. Zhou, Y., Hu, L., Grüner, G.: A method of printing carbon nanotube thin films. *Appl. Phys. Lett.* **88**(12), 123109 (2006)
190. Hilt, O., Brom, H.B., Ahlskog, M.: Localized and delocalized charge transport in single-wall carbon-nanotube mats. *Phys. Rev. B* **61**(8), R5129–R5132 (2000)
191. Zhang, D., Ryu, K., Liu, X., Polikarpov, E., Ly, J., Tompson, M.E., Zhou, C.: Transparent, conductive, and flexible carbon nanotube films and their application in organic light-emitting diodes. *Nano Lett.* **6**(9), 1880–1886 (2006)
192. Hellstrom, S.L., Lee, H.W., Bao, Z.: Polymer-assisted direct deposition of uniform carbon nanotube bundle networks for high performance transparent electrodes. *ACS Nano* **3**(6), 1423–1430 (2009)
193. Fan, J., Wan, M., Zhu, D., Chang, B., Pan, Z., Xie, S.: Synthesis and properties of carbon nanotube-polypyrrole composites. *Synth. Met.* **102**(1), 1266–1267 (1999)
194. Downs, C., Nugent, J., Ajayan, P.M., Duquette, D.J., Santhanam, K.S.V.: Efficient polymerization of aniline at carbon nanotube electrodes. *Adv. Mater.* **11**(12), 1028–1031 (1999)
195. Novoselov, K.S., Geim, A.K., Morozov, S.V., Jiang, D., Zhang, Y., Dubonos, S.V., Grigorieva, I.V., Firsov, A.A.: Electric field effect in atomically thin carbon films. *Science* **306**(5696), 666 (2004)
196. Gusynin, V.P., Sharapov, S.G.: Unconventional integer quantum hall effect in graphene. *Phys. Rev. Lett.* **95**(14), 146801 (2005)
197. Novoselov, K.S., McCann, E., Morozov, S.V., Fal'ko, V.I., Katsnelson, M.I., Zeitler, U., Jiang, D., Schedin, F., Geim, A.K.: Unconventional quantum Hall effect and Berry's phase of 2π in bilayer graphene. *Nat. Phys.* **2**(3), 177–180 (2006)
198. Siwal, S.S., Zhang, Q., Devi, N., Thakur, K.V.: Carbon-based polymer nanocomposite for high-performance energy storage applications. *Polymers* **12**(3) (2020)
199. Watcharotone, S., Dikin, D.A., Stankovich, S., Piner, R., Jung, I., Dommett, G.H.B., Evmenenko, G., Wu, S.-E., Chen, S.-F., Liu, C.-P., Nguyen, S.T., Ruoff, R.S.: Graphene–silica composite thin films as transparent conductors. *Nano Lett.* **7**(7), 1888–1892 (2007)
200. Trache, D., Thakur, V.K., Boukherroub, R.: Cellulose nanocrystals/graphene hybrids—a promising new class of materials for advanced applications. *Nanomaterials* **10**(8) (2020)
201. Hasija, V., Raizada, P., Sudhaik, A., Sharma, K., Kumar, A., Singh, P., Jonnalagadda, S.B., Thakur, V.K.: Recent advances in noble metal free doped graphitic carbon nitride based nanohybrids for photocatalysis of organic contaminants in water: a review. *Appl. Mater. Today* **15**, 494–524 (2019)
202. Platnieks, O., Gaidukovs, S., Neibolts, N., Barkane, A., Gaidukova, G., Thakur, V.K.: Poly(butylene succinate) and graphene nanoplatelet-based sustainable functional nanocomposite materials: structure-properties relationship. *Mater. Today Chem.* **18**, 100351 (2020)
203. Samarjeet, S., Sarit, G., Debkumar, N., Nishu, D., Venkata, K.P., Rasmita, B., Kaushik, M.: Synergistic effect of graphene oxide on the methanol oxidation for fuel cell application. *Mater. Res. Exp.* **4**(9), 095306 (2017)
204. Tung, V.C., Chen, L.-M., Allen, M.J., Wassei, J.K., Nelson, K., Kaner, R.B., Yang, Y.: Low-temperature solution processing of graphene–carbon nanotube hybrid materials for high-performance transparent conductors. *Nano Lett.* **9**(5), 1949–1955 (2009)
205. Wang, R., Sun, J., Gao, L., Xu, C., Zhang, J., Liu, Y.: Effective post treatment for preparing highly conductive carbon nanotube/reduced graphite oxide hybrid films. *Nanoscale* **3**(3), 904–906 (2011)
206. Peng, L., Feng, Y., Lv, P., Lei, D., Shen, Y., Li, Y., Feng, W.: Transparent, conductive, and flexible multiwalled carbon nanotube/graphene hybrid electrodes with two three-dimensional microstructures. *J. Phys. Chem. C* **116**(8), 4970–4978 (2012)
207. Zhang, R., Liao, Y., Zhou, Y., Qian, J.: A facile and economical process for high-performance and flexible transparent conductive film based on reduced graphene oxides and silver nanowires. *J. Nanopart. Res.* **22**(2), 39 (2020)
208. Miculescu, M., Thakur, V.K., Miculescu, F., Voicu, S.I.: Graphene-based polymer nanocomposite membranes: a review. *Polym. Adv. Technol.* **27**(7), 844–859 (2016)
209. Nair, R.R., Blake, P., Grigorenko, A.N., Novoselov, K.S., Booth, T.J., Stauber, T., Peres, N.M.R., Geim, A.K.: Fine structure constant defines visual transparency of graphene. *Science* **320**(5881), 1308 (2008)
210. Zhao, Y., Du, J., Li, Y., Li, X., Zhang, C., Zhang, X., Zhang, Z., Zhou, J., Pan, X., Xie, E.: Facile fabrication of flexible graphene-based micro-supercapacitors with ultra-high areal performance. *ACS Appl. Energy Mater.* **3**(9), 8415–8422 (2020)
211. Wang, Y., Zhou, W., Cao, K., Hu, X., Gao, L., Lu, Y.: Architected graphene and its composites: manufacturing and structural applications. *Compos. Part A: Appl. Sci. Manufact.* **106**177 (2020)
212. Chandel, N., Sharma, K., Sudhaik, A., Raizada, P., Hosseini-Bandegharai, A., Thakur, V.K., Singh, P.: Magnetically separable ZnO/ZnFe₂O₄ and ZnO/CoFe₂O₄ photocatalysts supported onto nitrogen doped graphene for photocatalytic degradation of toxic dyes. *Arabian J. Chem.* **13**(2), 4324–4340 (2020)
213. Bannov, A.G., Popov, M.V., Kurmashov, P.B.: Thermal analysis of carbon nanomaterials: advantages and problems of interpretation. *J. Therm. Anal. Calorimet.* **142**(1), 349–370 (2020)
214. Hu, Y., Peng, L.-M., Xiang, L., Zhang, H.: Flexible integrated circuits based on carbon nanotubes. *Acc. Mater. Res.* **1**(1), 88–99 (2020)
215. Shandilya, P., Sudhaik, A., Raizada, P., Hosseini-Bandegharai, A., Singh, P., Rahmani-Sani, A., Thakur, V., Saini, A.K.: Synthesis of Eu³⁺-doped ZnO/Bi₂O₃ heterojunction photocatalyst



- on graphene oxide sheets for visible light-assisted degradation of 2,4-dimethyl phenol and bacteria killing. *Solid State Sci.* **102**, 106164 (2020)
216. Walker, G.: A review of technologies for sensing contact location on the surface of a display. *J. Soc. Inf. Disp.* **20**(8), 413–440 (2012)
217. Park, C., Kim, S.W., Lee, Y.-S., Lee, S.H., Song, K.H., Park, L.S.: Spray coating of carbon nanotube on polyethylene terephthalate film for touch panel application. *J. Nanosci. Nanotechnol.* **12**(7), 5351–5355 (2012)
218. Kim, B.-J., Han, S.-H., Park, J.-S.: Sheet resistance, transmittance, and chromatic property of CNTs coated with PEDOT:PSS films for transparent electrodes of touch screen panels. *Thin Solid Films* **572**, 68–72 (2014)
219. Lee, W., Koo, H., Sun, J., Noh, J., Kwon, K.-S., Yeom, C., Choi, Y., Chen, K., Javey, A., Cho, G.: A fully roll-to-roll gravure-printed carbon nanotube-based active matrix for multi-touch sensors. *Sci. Rep.* **5**(1), 17707 (2015)
220. Islam, Z.U., Tahir, M., Syed, W.A., Aziz, F., Wahab, F., Said, S.M., R. Sarker, M., Md Ali, S.H., Sabri, M.F.: Fabrication and Photovoltaic Properties of Organic Solar Cell Based on Zinc Phthalocyanine. *Energies* **13**(4) (2020)
221. Rand, B.P., Peumans, P., Forrest, S.R.: Long-range absorption enhancement in organic tandem thin-film solar cells containing silver nanoclusters. *J. Appl. Phys.* **96**(12), 7519–7526 (2004)
222. Hadipour, A., de Boer, B., Blom, P.W.M.: Organic tandem and multi-junction solar cells. *Adv. Funct. Mater.* **18**(2), 169–181 (2008)
223. Hiramoto, M., Suezaki, M., Yokoyama, M.: Effect of thin gold interstitial-layer on the photovoltaic properties of tandem organic solar cell. *Chem. Lett.* **19**(3), 327–330 (1990)
224. Tanaka, S., Mielczarek, K., Ovalle-Robles, R., Wang, B., Hsu, D., Zakhidov, A.A.: Monolithic parallel tandem organic photovoltaic cell with transparent carbon nanotube interlayer. *Appl. Phys. Lett.* **94**(11), 113506 (2009)
225. Rowell, M.W., Topinka, M.A., McGehee, M.D., Prall, H.-J., Dennler, G., Sariciftci, N.S., Hu, L., Gruner, G.: Organic solar cells with carbon nanotube network electrodes. *Appl. Phys. Lett.* **88**(23), 233506 (2006)
226. Unalan, H.E., Hiralal, P., Kuo, D., Parekh, B., Amaratunga, G., Chhowalla, M.: Flexible organic photovoltaics from zinc oxide nanowires grown on transparent and conducting single walled carbon nanotube thin films. *J. Mater. Chem.* **18**(48), 5909–5912 (2008)
227. Kim, Y.H., Müller-Meskamp, L., Zakhidov, A.A., Sachse, C., Meiss, J., Bikova, J., Cook, A., Zakhidov, A.A., Leo, K.: Semi-transparent small molecule organic solar cells with laminated free-standing carbon nanotube top electrodes. *Sol. Energy Mater. Sol. Cells* **96**, 244–250 (2012)
228. Jiang, S., Hou, P.-X., Chen, M.-L., Wang, B.-W., Sun, D.-M., Tang, D.-M., Jin, Q., Guo, Q.-X., Zhang, D.-D., Du, J.-H., Tai, K.-P., Tan, J., Kauppinen, E.I., Liu, C., Cheng, H.-M.: Ultra-high-performance transparent conductive films of carbon-welded isolated single-wall carbon nanotubes. *Sci. Adv.* **4**(5), eaap9264 (2018)
229. Xu, Z., Wu, Y., Hu, B., Ivanov, I.N., Geohegan, D.B.: Carbon nanotube effects on electroluminescence and photovoltaic response in conjugated polymers. *Appl. Phys. Lett.* **87**(26), 263118 (2005)
230. Kazaoui, S., Minami, N., Nalini, B., Kim, Y., Takada, N., Hara, K.: Near-infrared electroluminescent devices using single-wall carbon nanotubes thin films. *Appl. Phys. Lett.* **87**(21), 211914 (2005)
231. Kim, J.-Y., Kim, M., Choi, J.-H.: Characterization of light emitting devices based on a single-walled carbon nanotube-polymer composite. *Synth. Met.* **139**(3), 565–568 (2003)
232. Woo, H.S., Czerw, R., Webster, S., Carroll, D.L., Ballato, J., Strevens, A.E., O'Brien, D., Blau, W.J.: Hole blocking in carbon nanotube-polymer composite organic light-emitting diodes based on poly (m-phenylene vinylene-co-2, 5-dioctoxy-p-phenylene vinylene). *Appl. Phys. Lett.* **77**(9), 1393–1395 (2000)
233. Qiu, S., Wu, K., Gao, B., Li, L., Jin, H., Li, Q.: Solution-processing of high-purity semiconducting single-walled carbon nanotubes for electronics devices. *Adv. Mater.* **31**(9), 1800750 (2019)
234. Wang, H., Bao, Z.: Conjugated polymer sorting of semiconducting carbon nanotubes and their electronic applications. *Nano Today* **10**(6), 737–758 (2015)
235. Dong, G., Zhao, J., Shen, L., Xia, J., Meng, H., Yu, W., Huang, Q., Han, H., Liang, X., Peng, L.: Large-area and highly uniform carbon nanotube film for high-performance thin film transistors. *Nano Res.* **11**(8), 4356–4367 (2018)
236. Wang, C., Zhang, J., Ryu, K., Badmaev, A., De Arco, L.G., Zhou, C.: Wafer-scale fabrication of separated carbon nanotube thin-film transistors for display applications. *Nano Lett.* **9**(12), 4285–4291 (2009)
237. Tian, B., Liang, X., Yan, Q., Zhang, H., Xia, J., Dong, G., Peng, L., Xie, S.: Wafer scale fabrication of carbon nanotube thin film transistors with high yield. *J. Appl. Phys.* **120**(3), 034501 (2016)
238. Huang, Q., Xia, J., Zhao, J., Dong, G., Liu, F., Meng, H., Liang, X.: Ultraviolet/ozone and oxygen plasma treatments for improving the contact of carbon nanotube thin film transistors. *Sci. Bull.* **63**(12), 802–806 (2018)
239. Liu, L., Ding, L., Zhong, D., Han, J., Wang, S., Meng, Q., Qiu, C., Zhang, X., Peng, L.-M., Zhang, Z.: Carbon nanotube complementary gigahertz integrated circuits and their applications on wireless sensor interface systems. *ACS Nano* **13**(2), 2526–2535 (2019)
240. Zhang, H., Xiang, L., Yang, Y., Xiao, M., Han, J., Ding, L., Zhang, Z., Hu, Y., Peng, L.-M.: High-performance carbon nanotube complementary electronics and integrated sensor systems on ultrathin plastic foil. *ACS Nano* **12**(3), 2773–2779 (2018)
241. Yang, Y., Ding, L., Han, J., Zhang, Z., Peng, L.-M.: High-performance complementary transistors and medium-scale integrated circuits based on carbon nanotube thin films. *ACS Nano* **11**(4), 4124–4132 (2017)
242. Huang, Q., Liu, F., Zhao, J., Xia, J., Liang, X.: Ambipolarity suppression of carbon nanotube thin film transistors. *Carbon* **157**, 358–363 (2020)
243. Li, H., Zhou, L.: Communication—high fidelity all-carbon based carbon nanotube thin film transistors. *ECS J. Solid State Sci. Technol.* **9**(4), 041010 (2020)
244. Lu, S., Zheng, J., Cardenas, J.A., Williams, N.X., Lin, Y.-C., Franklin, A.D.: Uniform and stable aerosol jet printing of carbon nanotube thin-film transistors by ink temperature control. *ACS Appl. Mater. Interfaces* **12**(38), 43083–43089 (2020)
245. Guo, C., Ouyang, J., Shin, H., Ding, J., Li, Z., Lapointe, F., Lefebvre, J., Kell, A.J., Malenfant, P.R.L.: Enrichment of semiconducting single-walled carbon nanotubes with indigo-fluorene-based copolymers and their use in printed thin-film transistors and carbon dioxide gas sensors. *ACS Sens* **5**(7), 2136–2145 (2020)
246. Sharma, S., Dutta, V., Singh, P., Raizada, P., Rahmani-Sani, A., Hosseini-Bandegharai, A., Thakur, V.K.: Carbon quantum dot supported semiconductor photocatalysts for efficient degradation of organic pollutants in water: a review. *J. Cleaner Prod.* **228**, 755–769 (2019)
247. Hong, E., Cho, W.: Low-power microwave annealing effect for random carbon nanotube network-based thin-film transistors and inverter circuits. *IEEE Electron Device Lett.* **41**(5), 733–736 (2020)
248. Chen, J., Mishra, S., Vaca, D., Kumar, N., Yeo, W.-H., Sitaraman, S., Kumar, S.: Thin dielectric-layer-enabled low-voltage



- operation of fully printed flexible carbon nanotube thin-film transistors. *Nanotechnol.* **31**(23), 235301 (2020)
249. Sun, D.-M., Liu, C., Ren, W.-C., Cheng, H.-M.: A review of carbon nanotube- and graphene-based flexible thin-film transistors. *Small* **9**(8), 1188–1205 (2013)
250. Siwal, S., Choudhary, M., Mpelane, S., Brink, R., Mallick, K.: Single step synthesis of a polymer supported palladium composite: a potential anode catalyst for the application of methanol oxidation. *RSC Adv.* **6**(53), 47212–47219 (2016)
251. Siwal, S., Matseke, S., Mpelane, S., Hooda, N., Nandi, D., Mallick, K.: Palladium-polymer nanocomposite: an anode catalyst for the electrochemical oxidation of methanol. *Int. J. Hydrogen Energy* **42**(37), 23599–23605 (2017)
252. Choudhary, M., Shukla, S.K., Taher, A., Siwal, S., Mallick, K.: Organic-inorganic hybrid supramolecular assembly: an efficient platform for nonenzymatic glucose sensor. *ACS Sustain. Chem Eng* (2014)
253. Meyyappan, M.V., Parthasarathy, V., Daniel, R.J.: Bio-interface behaviour of graphene and semiconducting SWCNT:C60 blend based nano photodiode for subretinal implant. *Biosurf. Biotribol.* **6**(2), 53–58 (2020)
254. Gabay, T., Ben-David, M., Kalifa, I., Sorkin, R., Abrams, Z.e.R., Ben-Jacob, E., Hanein, Y.: Electro-chemical and biological properties of carbon nanotube based multi-electrode arrays. *Nanotechnol.* **18**(3), 035201 (2007)
255. Shoval, A., Adams, C., David-Pur, M., Shein, M., Hanein, Y., Sernagor, E.: Carbon nanotube electrodes for effective interfacing with retinal tissue. *2*(4) (2009)
256. Yang, N., Chen, X., Ren, T., Zhang, P., Yang, D.: Carbon nanotube based biosensors. *Sens. Actuat. B Chem.* **207**, 690–715 (2015)
257. Feng, W., Ji, P.: Enzymes immobilized on carbon nanotubes. *Biotechnol. Adv.* **29**(6), 889–895 (2011)
258. He, H., Pham-Huy, L.A., Dramou, P., Xiao, D., Zuo, P., Pham-Huy, C.: Carbon nanotubes: applications in pharmacy and medicine. *BioMed Res. Int.* **2013**, 578290 (2013)
259. Muhulet, A., Miculescu, F., Voicu, S.I., Schütt, F., Thakur, V.K., Mishra, Y.K.: Fundamentals and scopes of doped carbon nanotubes towards energy and biosensing applications. *Mater. Today Energy* **9**, 154–186 (2018)
260. Rago, I., Rauti, R., Bevilacqua, M., Calaresu, I., Pozzato, A., Cibinel, M., Dalmiglio, M., Tavagnacco, C., Goldoni, A., Scaini, D.: Carbon nanotubes, directly grown on supporting surfaces, improve neuronal activity in hippocampal neuronal networks. *Adv. Biosystems* **3**(5), 1800286 (2019)
261. Wang, H.-J., Zhang, Y., Kato, S., Nakagawa, K., Kimura, F., Miyazawa, T., Wang, J.-Y.: HPLC-MS/MS: a potential method to track the in vivo degradation of zein-based biomaterial. *J. Biomedical Mater. Res. Part A* **106**(2), 606–613 (2018)
262. Rakesh, A.A., Nallin, S., Maheshwar, S., Madhuri, S.: Transparent conducting oxide films for various applications: a review. *Rev. Adv. Mater. Sci.* **53**(1), 79–89 (2018)
263. Contreras, M.A., Barnes, T., van de Lagemaat, J., Rumbles, G., Coutts, T.J., Weeks, C., Glatkowski, P., Levitsky, I., Peltola, J., Britz, D.A.: Replacement of transparent conductive oxides by single-wall carbon nanotubes in Cu(In, Ga)Se₂-based solar cells. *J. Phys. Chem. C* **111**(38), 14045–14048 (2007)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

