

DEPENDENCE OF MATERIAL QUALITY ON PERFORMANCE OF FLEXIBLE TRANSPARENT CONDUCTING FILMS WITH SINGLE-WALLED CARBON NANOTUBES

HONG-ZHANG GENG^{*}, KI KANG KIM[†], KYU LEE, GIL YONG KIM, HA KYU CHOI, DAE SIK LEE, KAY HYEOK AN and YOUNG HEE LEE[‡] Department of Nanoscience and Nanotechnology Department of Physics, and Center for Nanotubes and Nanostructured Composites

Sungkyunkwan Advanced Institute of Nanotechnology

Sungkyunkwan University Suwon 440-746, Korea *ghzh88@skku.edu [†]w012230@skku.edu [‡]leeyoung@skku.edu

YOUNGKYU CHANG $\ ^{\ },$ YOUNG SIL LEE, BYEONGYEOL KIM and YOUNG JUN LEE

Chemical R&D Center Research Institute of Chemical and Electronic Materials Samsung Cheil Industries, Inc., Uiwang 437-711, Korea [§]y.chang@samsung.com

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Several single-walled carbon nanotubes (SWCNTs) prepared by different methods have been used to investigate the material dependence on the optimal film performance of flexible transparent conducting films. The nanotubes were dispersed in water with sodium dodecyl sulfate by sonication. These SWCNT solutions were then sprayed onto the Poly(ethylene terephthalate) substrate by a spray coater to form the film. Several factors such as purity, diameter, defects, metallicity, and degree of dispersion were evaluated individually to examine how they affect the film performance. We found that the metallicity of SWCNTs and the degree of dispersion are the most crucial factors in determining the film performance. We also proposed a material quality factor to estimate the material quality of SWCNTs as a figure of merit for the film performance.

Keywords: Transparent conducting films; carbon nanotubes; material quality factor; metallicity; degree of dispersion.

1. Introduction

Interest in flexible transparent conducting films (TCFs) has been growing recently mainly due to the demand for electrodes incorporated in flexible or wearable displays in the future.¹ The current technology adopts indium-tin oxide (ITO) for TCFs, which meets the requirement of low resistance and high transmittance. Yet, bending of the ITO film generates cracks in the film, resulting in poor flexibility.² This is a serious drawback in flexible display applications. The carbon nanotube (CNT) is a new functional material that can be treated as a graphitic sheet with a hexagonal lattice being wrapped into a cylinder.^{3,4} It has a high aspect ratio of typically 10000 or greater, with a diameter of a few nanometers. It is generally known that CNTs have a high elastic modulus of 1–2 TPa as well as high electrical conductivity of 1000 times higher than copper wire.5-7 The CNTs are capable of forming naturally robust random networks in the film and provide low sheet resistance and high transmittance with a minimal amount of CNTs.⁸ CNT films have been known to exhibit excellent bending characteristics over the conventional ITO film. These structural and physical properties of CNTs are superb features for flexible TCFs, providing high performance of transparency and conductivity. Nevertheless, the performance of the CNT-based TCFs strongly relies on CNTs itself and the materials with various treatments and film preparation conditions.^{2,9–16} The understanding of the material dependence and film fabrication methods to determine the sheet resistance and transmittance is still at an early stage.

The fabrication of TCFs includes three steps: (i) the CNT treatment, (ii) the CNT-solution preparation, and (iii) the film preparation. The choice of CNTs, the degree of purity and the defects of CNTs, and further treatment of CNTs are presumably important factors in determining the film performance. The CNTs are easily bundled with a diameter of typically a few tens nanometers due to their strong van der Waals interactions ($\sim 1000 \, \text{eV}$) originating from the micrometer long CNTs.^{17–19} The macrodispersion (small-size bundles) or the nanodispersion (dispersion into individual nanotubes) is strongly desired in order to minimize the absorbance.^{20,21} The choice of solvents and the related dispersants are crucial factors in achieving the best dispersion conditions.²² Once the CNTs are dispersed, the film preparation is another important

step to consider since this determines the networking of CNTs and hence the sheet resistance.

The purpose of this paper is to derive the decisive factors which determine the film performance of CNT-based TCFs. The material parameters of several single-walled CNTs (SWCNTs) synthesized by different methods such as arc discharge (Arc), catalytic chemical vapor deposition (CVD), high pressure carbon monoxide (HiPCO), and laser ablation (Laser) were systematically analyzed in this study to investigate the material dependence (purity, defects and metallicity of SWCNTs) and the degree of dispersion of SWCNTs in solvent. After the SWCNT powder was characterized, each of them was dispersed in deionized water with sodium dodecyl sulfate (SDS) by sonication followed by a spray process to fabricate the SWCNT film onto Poly(ethylene terephthalate) (PET: thickness \approx $100 \,\mu\text{m}$) substrate. By analyzing the SWCNT film performance varying with the SWCNT parameters, we found that the metallicity of the SWCNTs extracted from G'-band intensity of Raman spectroscopy and the degree of dispersion in the solution are the most decisive factors in determining the film performance. We also propose a material quality factor similar to a mobility of nanotubes as a figure of merit to evaluate the material quality of SWCNTs.

2. Experimental

Four different SWCNTs were used. The CVD SWCNTs were purchased from SouthWest Nano-Technologies, Inc. HiPCO SWCNTs and Laser SWCNTs were from Carbon Nanotechnology, Inc. Arc SWCNTs were from Iljin Nanotech Co. Ltd. A schematic diagram of the experimental procedures to prepare the TCFs is shown in Fig. 1. This involves dispersion of SWCNTs in solution, centrifugation to remove the large size bundles and metal catalysts, and the film formation by a spray coater.²³ Deionized water was used to disperse SWCNTs with sonication and centrifugation. We have changed the SWCNT and SDS concentration and sonication time for better dispersion while keeping the nozzle of spray gun from being clogged. In this work, each type of SWCNT (concentration $0.3 \,\mathrm{mg/ml}$) was dissolved in water with SDS (Sigma-Aldrich, concentration 3 mg/ml) and sonicated in a bath type sonicator (Power sonic 505) at 400 W for 10 h. The SWCNT solution was centrifuged at 10000 g for 10 min by centrifuger (Hanil



Fig. 1. A schematic diagram of the experimental procedure to prepare the TCFs.

Science Industrial, MEGA 17R). The upper 50% of the supernatant solution was carefully decanted for characterization. The SWCNT supernatant was directly sprayed with air brush pistol (GUNPIECE GP-1) onto the PET substrate to form TCFs. During the spray process, the PET substrate holder was kept at 100°C to accelerate evaporation of the fine droplets on the surface. Increase in spray times lead to thick films. When the spray process was terminated, the TCF was immersed into deionized water for 10 min to remove the surfactant and then it was dried in a dry oven at 80°C for 30 min. This process was repeated twice to further remove surfactants and enhance adhesion between SWCNTs and PET film.

The SWCNT powders were characterized by field emission scanning electron microscopy (FE-SEM-JEOL 6700F), transmission electron microscopy (JEOL 2010F high-resolution TEM, 200 KeV), thermogravimetric analysis (TGA-Seiko Exstar 6000 (TG/DTA6100)), and Raman spectroscopy (Renishaw RM1000). FE-SEM was used to analyze the morphology of the SWCNT powder and TCFs. TEM was used to obtain the diameters of SWCNTs. For TGA, the powder sample was preheated in vacuum to remove humidity and was heated at a rate of $5^{\circ}C/min$ in air flow. The SWCNT powder was used for Raman measurements with laser excitation energies of $514 \,\mathrm{nm}$ (2.41 eV) and $633 \,\mathrm{nm}$ (1.96 eV), equipped with a notch filter of $50 \,\mathrm{cm}^{-1}$ cutoff frequency for ensuring a low energy radial breathing mode (RBM). Absorbance of the SWCNT supernatant filled in a quartz cell with a path length of 1 mm was recorded by UV-VIS-NIR spectrophotometer

(Cary-5000) in the wavelength range from 200 to 1400 nm. The transmittance of TCF was recorded in the visible range (400–800 nm). Measurements of the sheet resistance were carried out by four-point probe method (Keithley 2000 multimeter) at room temperature.

3. Results and Discussion

Our primary goal was to evaluate how the material conditions affect the film performance. For this purpose, we chose four different types of SWCNTs. Once the prepared SWCNT powder was dispersed in deionized water with SDS, as described in the experimental section, the supernatant solution was spraved onto PET film to form thin SWCNT film. known hereafter as a TCF where "Arc TCF" is a TCF fabricated with SWCNTs synthesized by arc discharge and so on. The thickness was controlled by the number of spray times. Figure 2 summarizes the TCF performance with the sheet resistance and transmittance at 550 nm. The number of data points in each line corresponds to the number of samples with different film thicknesses. The film performance changes dramatically for different types of SWCNTs. For instance, it seems that under the current approach, the TCFs fabricated with Arc SWCNTs result in the best film performance. The sheet resistance of the Arc TCF is $\sim 160 \,\Omega/\mathrm{sq}$ at a transmittance of 80% and is comparable with the previous data which validates our approach.¹⁴ Thus, the Arc TCFs can be used in a



Fig. 2. Characteristic curves of sheet resistance-transmittance of TCFs fabricated by various SWCNTs. Each curve contains several data points from TCFs with different number of sprays of SWCNT solution dispersed in deionized water with SDS. More sprays were applied to TCFs with data points in the left of the figure with low transmittance. Transmittance at 550 nm was selected for comparison.

wide range of applications from touch panels to electrodes for future flexible displays. However, in this work, we focus on what material parameters affect this behavior rather than on which TCF shows the best performance.

3.1. Purity and diameter

The morphologies of the four SWCNT powders used in our study are illustrated by FE-SEM and TEM as shown in Fig. 3. The bundle structures are clearly visualized in insets. The diameters of individual nanotubes in CVD and HiPCO SWCNTs were about 1 nm, smaller than those (~ 1.4 nm) of Laser and Arc SWCNTs, as determined from TEM images. The CVD SWCNTs had the smallest average bundle size, as estimated from the SEM images, whereas the Laser sample exhibited the largest average bundle size among samples. Carbonaceous particles on the SWCNT bundles are present in the CVD SWCNTs. The Arc SWCNTs have relatively well-defined crystallinity without amorphous carbons on the tube walls, although the bundle size of the Arc sample is smaller than that of the Laser sample. The presence of carbonaceous particles on

the nanotube walls is an important factor for the application of TCFs since it determines the contact resistance between SWCNT networks.^{24–26} Nevertheless, only the morphologies cannot quantify the material qualities.

The SWCNT purity can be obtained from the TGA. Figure 4 presents the TGA and differential TGA of our samples. The SWCNTs start to burn off in air with increasing temperature. The burning temperature, which can be defined as the peak value in the differential curve of TGA, varies with several parameters such as the content of metals, the bundle diameter of SWCNTs, the number of walls, and the crystallinity of SWCNTs.²⁷ The unusual endothermic burning behavior is typically observed in the sample with high metal content, which can be seen in the CVD SWCNTs in Fig. 4(a). The Laser SWCNTs in Fig. 4(c) reveal two peaks in the differential TGA. The first peak of the DTG curve is identified as the burning temperature of amorphous carbons.²⁸ The second peak can be regarded as the burning temperature of SWCNTs, here the burning temperature is very low primarily due to the presence of large amount of catalysts ($\sim 10 \text{ wt\%}$). The burning temperature is also related to the number



Fig. 3. FE-SEM (scale bar: 200 nm) and TEM (inset, scale bar: 20 nm) images of: (a) CVD-, (b) HiPCO-, (c) Laser-, and (d) Arc-SWCNT powders.



Fig. 4. TGA and differential TGA of the four SWCNT powders.

of defects on the SWCNT walls. This can be analyzed in Raman spectroscopy. The remaining material at 900°C is the metal oxide. Each SWCNT samples contained some amount of catalyst. The purity can be determined by the weight percent of the metal oxides with respect to all carbon materials including amorphous carbons.²⁹ High transition metal content results in the degradation of conductivity, as shown in Fig. 5(a). The sheet conductance of the TCFs at transmittance of 70% and 80% is calculated from Fig. 2 for comparison.

It is interesting to note that the influence of the purity of the SWCNT is less deterministic, particularly in CVD and HiPCO SWCNTs, whereas the diameter has a strong correlation to the sheet conductance of SWCNT film as shown in Fig. 5. The sheet conductance of the film increases consistently with increasing diameters of nanotubes in Fig. 5(b). Bandgap E_g of semiconducting nanotubes is inversely proportional to the diameter D, $E_g = 2a_{c-c}\gamma_0/D$ (eV), where a_{c-c} is 0.142 nm and γ_0 is an empirical tight-binding parameter taken as 2.9 eV.³⁰ The conductivity of SWCNTs can generally be simply expressed as

$$\sigma = n e \mu_n + p e \mu_p \,, \tag{1}$$

where n and p are the *n*-type (electrons) and *p*-type (holes) carrier concentrations, respectively, and μ_n and μ_p are the respective electron and hole mobility. The mobility is dominated by a succession of random scattering from collisions with lattice atoms, impurity atoms, and other scattering centers. The intrinsic carrier concentration decreases exponentially with bandgap, $n_i = n_0 \exp(-E_q/2k_BT)$, where k_B and T are the Boltzmann constant and temperature of the system, respectively. The *p*-type and *n*-type nanotube carrier concentrations are, $p = n_i \exp[(E_i - E_f)/k_B T]$, and $n = n_i \exp[(E_f - E_f)/k_B T]$ $E_i)/k_BT$, where the intrinsic Fermi level, E_i , is frequently used as a reference level when the extrinsic semiconductors are discussed with a Fermi level of E_f . The conductivity is proportional to the carrier concentration, $\sigma \sim \exp(-E_g/2k_BT)\exp[(E_i - E_g/2k_BT)]$ $(E_f)/k_BT$ for semiconducting nanotubes. For the intrinsic semiconducting nanotubes, $E_i = E_f$.

On the other hand, in the metallic nanotubes, π and π^* overlap at the Fermi level, i.e., the metallic nanotubes are always metallic independent of the diameters. Nevertheless, it has been suggested that the nanotubes are usually bundled and a pseudogap of ~ 0.1 eV is open due to the tube–tube



Fig. 5. The sheet conductance of TCFs at transmittance of 70% and 80% versus (a) purity and (b) diameter of SWCNT powders. The dotted lines are guides for eye to denote the trend.

interaction.³¹ This pseudogap is small compared to the direct bandgap of semiconductors with diameters of 1–1.4 nm corresponding to bandgaps of 0.7–1.0 eV.⁵ The pseudogap E_{pg} in the metallic SWCNT bundles is inversely proportional to the tube diameter via $E_{pg} \approx 0.105/D$ (eV) after fitting to the observed values.³² Thus, the conductivity of the metallic nanotubes reveals the similar diameter dependence to semiconducting ones, $\sigma \sim$ $\exp(-E_{pg}/2k_BT)$, explaining why the conductivity of the film increases with diameter of SWCNTs as shown in Fig. 5(b).

3.2. Raman spectroscopy: Defects and metallicity

Figure 6 shows the Raman spectra of SWCNTs at excitation energies of 514 nm and 633 nm. The



Fig. 6. Raman spectra of the SWCNT powders at an excitation energy of (a) 514 nm and (b) 633 nm. Each region of van Hove singularities is provided in a box. The shaded area indicates the areal portion of the metallic and the semiconducting SWCNTs.

metallicity of each SWCNTs can be assigned from the radial breathing modes (RBMs). Since the position of van Hove singularities is dependent specifically on the diameter and chirality, the metallicity of the excited SWCNTs can be determined thoroughly.^{5,33-35} At 514 nm, in Fig. 6(a), the Laser and Arc SWCNTs reveal the semiconducting behavior exclusively, as can be seen in RBMs. On the other hand, CVD and HiPCO SWCNTs contain both metallic and semiconducting nanotubes. The abundance of the metallic nanotubes is further evidenced by the presence of a long tail at the lower energy side in the G-band, i.e., the Fano line representing the metallic contribution.³⁶ At 633 nm, in Fig. 6(b), the Laser and Arc SWCNTs pick up mostly metallic SWCNTs, whereas the CVD SWC-NTs retain mostly semiconducting properties (less prominent Fano line) and the HiPCO SWCNTs contain both the metallic and the semiconducting behaviors. In addition to RBMs and G-band, Dband and G'-band are also present in all types of SWCNTs. A similar trend was also observed at 514 nm excitation. The D-band near 1320 cm^{-1} represents the contribution of defects.³⁷ The G'-band is the second-order Raman signal, the first overtone of the D-band. The double-resonance giving rise to G' modes involves two phonons, whereas the D mode involves a phonon and a defect consisting of an elastic and inelastic scattering process.³⁸

Our results clearly show the strong dependence of the G'-band intensity on the metallicity, in good agreement with the previous report.^{39,40} It is also noted in our samples that the intensity of the G'-band is strongly correlated to the intensity of metallic peaks in RBMs. Despite the abundance of metallicity, the presence of defects on the nanotube walls that may act as scattering centers degrades the conductivity of the SWCNT network. The intensity of the D-band indicates the amount of defects on the nanotube walls. Therefore, an appropriate parameter to express conductivity of nanotubes for SWCNTs is the intensity ratio, G'band/D-band. High abundance of metallicity and few defects on the nanotube walls will be desired for high conductivity of the SWCNT films. Figure 7 shows the sheet conductance of the four types of SWCNT films at transmittance of 80% as a function of intensity ratio of G'-band/D-band of SWCNT powder at the excitation energies of 514 nm and 633 nm. One finds that there is a strong dependence of the conductivity on the intensity ratio of G'-band/D-band. Yet, some deviations are observed near the region of low sheet conductance.

From these analyses, it may be useful to extract a practical parameter as a figure of merit to evaluate



Fig. 7. The sheet conductance of TCFs at a transmittance of 80% versus intensity ratio of G'/D-band of the SWCNT powders from Raman spectroscopy at excitation energies of 514 nm (2.41 eV) and 633 nm (1.96 eV).

an effective material quality of SWCNTs for the film performance. The purity affects the conductivity. The diameter contributes to the conductivity via bandgap described in the previous paragraph. More defects reduce the mean free path of carriers and decrease the mobility of carriers in nanotubes. The intensity ratio of G'-band/D-band may represent the mobility of the carriers. The conductivity is proportional to the metallicity of nanotubes and inversely proportional to the number of scattering centers or defects. Here, we define an effective material quality factor Q_m that governs the conductivity of SWCNTs

$$Q_m = P \times \left(e^{-E_{pg}/2k_BT} \times \overline{\sum I_M} + e^{-E_g/2k_BT} \times e^{(E_i - E_f)/k_BT} \times \overline{\sum I_S} \right), \quad (2)$$

where $E_g = 0.82/D$ (eV) and $E_{pg} = 0.105/D$ (eV) from the previous paragraph, D is the average diameter of individual SWCNTs and P is the purity of the sample. The intensity ratio of G'/D was averaged over the excitation energies of Raman spectroscopy for each metallic and semiconducting nanotubes. Here I_S (I_M) is defined as

$$I_S(I_M) = I_{G'\!/\!D} \times \frac{A_S(A_M)}{A_M + A_S}, \qquad (3)$$

where $A_S(A_M)$ is the areal intensity of semiconducting (metallic) peaks of RBMs from Raman shift in Fig. 6 (Fig. 6(a) shows one example of obtaining the areal ratio from HiPCO SWCNTs at 514 nm). The first term in Eq. (2) represents the contribution from metallic tubes. The second exponential term represents the carrier concentration and the third exponential term represents the mobility that changes with doping effect for semiconducting tubes. Thus, this formula resembles the conductivity of Eq. (1). Only two wavelengths were used in our study but it seemed satisfactory to explain the TCF performance in terms of Q_m . The abundance of metallic nanotubes is implicitly expressed in the intensity ratio of G'/D. Since the exponent of metallic nanotubes is much greater than that of semiconducting nanotubes with typical diameters of 1-2.0 nm, the second term can be negligible in Eq. (2) in intrinsic nanotubes when $E_i \approx E_f$. The semiconducting nanotubes generally are sensitive to the environment invoking a doping effect. In such cases, the Fermi level can be shifted and the second term may not be negligible. Although the pseudogap of metallic nanotubes can be affected



Fig. 8. The sheet conductance of TCFs at transmittance of 70% and 80% versus material quality factor defined in the text.

by a doping effect, 41,42 we did not consider it in Eq. (2), since it is relatively small in comparison to that of semiconducting nanotubes. We calculated the material quality factor Q_m in case of $E_i \approx E_f$. Figure 8 shows the sheet conductance of TCFs at transmittance of 70% and 80% as a function of the material quality factor Q_m . It is clearly observed that the sheet conductance reveals a linear relationship with the material quality factor. Although this empirical formula is not rigorous, it can provide at least a means of estimating material quality that governs the conductivity of the SWCNT TCFs. For instance, large diameter, higher purity, less defects (lower intensity of D-band), and more metallic nanotubes (higher intensity of G'-band) will give better conductivity of the SWCNT TCF. From this point of view, the Arc TCF is the best sample providing the highest conductivity in comparison to TCFs made by other types of SWCNTs considered in this work, as can be seen from Fig. 2. However, it may be conjectured that different optimization conditions for dispersion and film preparation may change the TCF properties. In spite of such a possibility, the argument for the material quality dependence described above still holds true. For a direct comparison, at a transmittance of 80%, the Arc TCF shows the lowest sheet resistance of about $160 \,\Omega/\mathrm{sg}$, whereas the CVD TCF shows the highest resistance. The trend of the change in sheet conductance is similar at different transmittance regions, although the slopes are different. This suggests that our definition of the effective material parameter is quite understandable from a material point of view to describe the TCF performance.

3.3. Degree of dispersion

Once the material quality is determined, there is still another process of film preparation as described in Fig. 1. In order to see the dependence of the TCF morphology on the TCF performance, the FE-SEM images are shown in Fig. 9. The CVD and HiPCO TCFs reveal coagulation of CNT network by excess SDS that still remained in the sample even after repeated washing. In spite of the equivalent washing conditions, the Laser TCF shows less remaining SDS with clear visibility of the bundles. The Arc TCF shows almost no SDS with well defined bundles. The reason why the excess SDS particles are aggregated in the TCFs is not clear at this moment. It may be ascribed to the abundant defects that enhance interaction of SDS with the SWCNT walls. This may be evidenced by the D-band in Raman spectra in Fig. 6. Since the SDS is an insulating material, the amount of remaining SDS is always crucial with an excess amount being detrimental for the TCF conductivity. The sheet resistance of the TCF can be modeled by the sum of the series resistance of the SWCNTs themselves and number of cross junctions formed between SWCNTs. The cross junction is connected via van der Waals interaction. The conductivity of the film is dominated by inter-tube hoping electron transport which is dominated by the degree of dispersion of the nanotubes. The electrons transport via the hoping mechanism through these junctions. Again, this transport is hindered by the presence of insulating SDS in the cross junctions.

The degree of dispersion is mainly determined by sonication time and surfactant, which can be assessed by simply noting the size of SWCNT bundles. Large bundle size is an indication of poor SWCNT dispersion. Poor dispersion leads to precipitation during centrifugation where the large bundles of SWCNTs precipitate. As a consequence, fewer SWCNTs are left in the supernatant, resulting in less absorption (better transparency) in the UV-absorbance.⁴³ This can be seen in Fig. 10(a), where Arc SWCNTs solution were compared. The solution II was subjected to a shorter sonication time and lower centrifugation speed than solution I. Thus, one method to control the bundle size of SWCNTs left in the supernatant is to change the centrifugation speed. Higher centrifugation speed leads to small bundle sizes in the supernatant, since the larger bundles precipitate, however, the concentration of SWCNTs is lower. This provides a large

Dependence of Material Quality on Performance of Flexible Transparent Conducting Films with SWCNTs 165



Fig. 9. The FE-SEM images of the as-prepared TCFs using four types of SWCNTs (scale bar: $1 \mu m$).



Fig. 10. (a) Absorbance of the Arc SWCNT solution, where in comparison to solution I, shorter sonication time and lower centrifugation speed were used for solution II. (b) The sheet resistance and transmittance from TCFs fabricated by solutions I and II and the corresponding FE-SEM images (scale bar: 500 nm). The solid circles indicate technical targets for touch screen (TS) and flat panel displays (FPD).

number of network junctions giving to smaller sheet resistance and less absorbance (or higher transmittance), as illustrated in Fig. 10, where the TCFs in curves named Arc-I and Arc-II with corresponding FE-SEM images were fabricated using solution-I and solution-II, respectively. The enhanced degree of entanglement of SWCNT networks clearly demonstrates the importance of dispersion. Although a better supernatant dispersion and thus better TCF transmittance is usually achieved for higher centrifugation speeds, there is a tradeoff since so many SWCNTs are lost during high centrifugation speed. However, there is a limit to the centrifugation speed since not only the large bundles but also small SWCNT bundles with longer lengths are lost. In fact, after very high centrifugation speed, SWCNTs with only low aspect ratio were found in the supernatant. This may increase the critical density corresponding to the percolation threshold.¹³ If SWCNT bundles with low aspect ratio are the majority in the supernatant, the sheet resistance of TCFs is high, even though the transmittance is high. An alternative solution preparation method with smalldiameter bundle sizes of SWCNTs and long lengths is desired. The performance of our TCFs matches the demand for touch screen applications and is very close to meeting the requirements for flat panel displays. A further improvement in the film performance which could help the quality of TCFs become applicable to flat panel displays and other devices may be realized by choosing highly conductive SWCNTs evaluated by material quality factor and by enhancing the degree of dispersion of SWCNTs using different surfactants in various solvents.

4. Conclusions

In conclusion, the dependence of the material qualities on the flexible TCFs was investigated by analyzing four types of SWCNTs and the TCFs incorporating these SWCNTs. The TCFs were fabricated by a simple spray coating method. From a thorough analysis of material qualities such as purity, diameter, defects, metallicity of the sample, and the degree of dispersion of SWCNTs, we found that diameter, the metallicity of SWCNTs, and the degree of dispersion are the most important factors influencing the TCF conductivity and transmittance. We proposed a material quality factor that governs the conductivity of SWCNTs by using the diameter, purity, and the intensity ratio of G'-band to D-band from Raman spectroscopy. The material quality factor was directly correlated to the performance of the TCFs including doping effect.

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