Computational study of geometry-dependent resistivity scaling in single-walled carbon nanotube films

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(Received 13 November 2006; revised manuscript received 30 January 2007; published 29 March 2007)

We study the geometry-dependent resistivity scaling in single-walled carbon nanotube films as a function of nanotube and device parameters using Monte Carlo simulations. We first demonstrate that these simulations can model and fit recent experimental results on the scaling of nanotube film resistivity with device width. Furthermore, we systematically study the effect of four parameters; namely, tube-tube contact resistance to nanotube resistance ratio, nanotube density, nanotube length, and nanotube alignment on the film resistivity and its scaling with device width. Stronger width scaling is observed when the transport in the nanotube film is dominated by tube-tube contact resistance. Increasing the nanotube density decreases the film resistivity strongly and results in a higher critical exponent and a lower critical width. Increasing the nanotube length also reduces the film resistivity, but increases both the critical exponent and the critical width. In addition, the lowest resistivity occurs for a partially aligned rather than perfectly aligned nanotube film. Increasing the degree of alignment reduces both the critical exponent and the critical width. We systematically explain these observations, which are in agreement with previous experimental results, by simple physical and geometrical arguments. We also observe that, near the percolation threshold, the resistivity of the nanotube film exhibits an inverse power-law dependence on all of these parameters, which is a distinct signature of percolating conduction. However, the strength of resistivity scaling for each parameter is different, and it depends on how strongly a particular parameter changes the number of conduction paths in the film. Monte Carlo simulations, as presented in this paper, can help elucidate the effects of various parameters on percolating transport in films made up of one-dimensional conductors, which is an essential step towards understanding and characterizing the performance of these nanomaterials in electronic and optoelectronic devices.

DOI: 10.1103/PhysRevB.75.125432

PACS number(s): 72.60.+g, 85.35.Kt, 73.63.Fg

I. INTRODUCTION

Single-walled carbon nanotube (CNT) networks and films have recently attracted significant research attention due to their interesting properties. They are transparent, conductive, and flexible and have uniform physical and electronic properties since individual variations in nanotube diameter and chirality are ensemble averaged. As a result, the reproducibility and reliability problems found in devices based on individual nanotubes are solved, and CNT-film-based devices can be mass produced in a cost-effective manner. Several promising applications of CNT films have recently been demonstrated, such as thin film transistors, flexible microelectronics, chemical sensors, and optoelectronic devices.

One of the important characteristics of CNT films, which needs to be taken into account for any device application, is that their resistivity depends strongly on nanotube and device parameters due to percolating conduction. For example, it has been recently shown experimentally that resistivity of nanotube networks depends strongly on device length, nanotube density, and nanotube length in the film, and the resistivity of nanotube films depends strongly on the film thickness. It has also been shown experimentally that the resistivity of carbon nanotube/polymer composites depends strongly on nanotube alignment in the composite. Furthermore, we have recently reported experimental results demonstrating that the resistivity of nanotube films exhibits an inverse power-law dependence on device width and film thickness near the percolation threshold.

In order to investigate the physical and geometrical origins of these experimental findings more systematically, simulation and modeling techniques have to be employed. Although there have been several experimental reports on CNT films and networks, very little work has been done on their modeling and simulation. In a previous numerical simulation work, resistivity scaling with device length has been studied for different nanotube densities. In another work, the effect of nanotube alignment on the percolation probability of nanotube/polymer composites has been calculated by two-dimensional (2D) Monte Carlo simulations. However, a systematic study of the effects of various nanotube and device parameters on the CNT film resistivity and its scaling with device width has not been reported previously.

In this paper, we study the geometry-dependent resistivity scaling in CNT films using Monte Carlo simulations by randomly generating nanotubes on stacked 2D rectangular planes. We first demonstrate that these simulations can model and fit the recent experimental results on the scaling of nanotube film resistivity with device width. Then, we systematically study the effect of four parameters; namely, tube-tube contact resistance to nanotube resistance ratio, nanotube density, nanotube length, and nanotube alignment on the CNT film resistivity and its scaling with device width. We then explain these simulation results by simple physical and geometrical arguments. A better physical understanding of geometry-dependent percolating transport in single-walled carbon nanotube films is essential for characterizing and evaluating their performance in potential electronic and optoelectronic device applications.

II. COMPUTATIONAL METHOD

Simulation of the electrical properties of the nanotube film was performed by randomly generating the nanotubes.
of the type of junction, following the simplified approach of Ref. 24.

After the locations of the junctions are determined, coordinates of the neighbors of each internal node, which are defined as other nodes that are in direct electrical contact with that node, are located. By this definition, a node must be connected by nanotube segments to all of its neighbors. The resistance between two neighboring nodes can easily be determined by calculating the length of the nanotube segment connecting them. The resistance of a single-walled carbon nanotube segment, $R_{CNT}$, as a function of its length $l$ is calculated using the expression

$$R_{CNT} = R_0 \frac{\lambda + l}{\lambda},$$

where $R_0$ is the theoretical contact resistance at the ballistic limit (~6.5 kΩ) and $\lambda$ is the mean free path, assumed to be 1 μm in our simulations.27,28

Writing Kirchoff’s current law (KCL) at each internal node for a mesh with $n$ internal nodes, we get a set of $n$ equations with $n$ unknowns, where the $n$ unknowns are the voltages $V_n$ at each node. The voltages applied to the source and drain electrodes set up the necessary boundary conditions. Once the voltage at each node is solved, the total current in the film is calculated by a summation over the currents flowing into the drain boundary nodes. Finally, the resistance, and, as a result, the resistivity $\rho$ of the nanotube film in the linear regime, is calculated by dividing the voltage drop between the source and drain electrodes by the total current in the film.

For each data point presented in this paper, 200 or more independent nanotube film configurations were randomly generated and their results were averaged in order to remove statistical variations in the data calculated from different realizations of the nanotube film. In addition, the percolation probability $P$, defined as the probability that the nanotube film is conducting (i.e., the probability of finding at least one conducting path between the source and drain electrodes) is also calculated to complement the resistivity data.

The model can be improved in several ways if a more precise simulation is required. First, our model ignores non-linear effects at high bias voltages28 by assuming a fixed nanotube resistance independent of bias voltage. This dependence of $R_{CNT}$ on $V_n$ can be included by solving the current continuity equation self-consistently with the Poisson equation in a recursive manner. Second, metallic and semiconducting nanotubes could be separately tracked and different contact resistance values could be used for SS, MM, and MS junctions instead of an “effective” contact resistance $R_{JCT}$. Furthermore, a more accurate model can be developed for MS Schottky junctions by taking into account the variation of the depletion region in the semiconducting nanotube with the voltage at the contact node.29 Finally, a Gaussian length distribution could be used for the nanotubes instead of a fixed “effective” length $l_{CNT}$.

Our simulation results presented below show that, despite their relative simplicity, the models we have used can capture the essential physics of the experimentally observed resistiv-
III. RESULTS AND DISCUSSION

Figure 2(a) shows the normalized resistivity of the CNT film as a function of device width $W$. The symbols are the experimental data points from our previous work$^{23}$ for a nanotube film with device length $L=7$, 50, or 200 $\mu$m (labeled by different symbols) and average thickness $t=15$ nm. The solid line represents the simulation best fit to the experimental data with $R_{\text{ratio}}=100$ and $n=2$ $\mu$m$^{-2}$. The other simulation parameters are $L=7$ $\mu$m, $l_{\text{CNT}}=2$ $\mu$m, and $t=15$ nm. (b) Log-log plot of normalized resistivity versus device length $L$ for three different nanotube densities $n$, as labeled by different symbols in the plot, calculated using our simulation code for a device with $W=2$ $\mu$m.

The average thickness $t$ of the film is ±15%. The extracted value for the resistance ratio can also be compared to estimates from previous work. In particular, it has been shown by several experiments that the tube-tube junction resistance is larger than the resistance of the nanotube layer itself. As a result, to fit the experimental data of Fig. 2(a), below a critical width $W_C$ of around 2 $\mu$m, the resistivity starts to increase strongly above its minimum saturation value, and near the percolation threshold the experimental data points can be characterized by an inverse power law of the form

$$
\rho \propto W^{-\alpha},
$$

where $\alpha$ is the critical exponent for width scaling. As we will show in detail later, changing the resistance ratio affects only the critical exponent, whereas changing the nanotube density changes both the critical exponent and the critical width. As a result, the nanotube density was varied to match the critical width $W_C$, and then the resistance ratio was varied to match the critical exponent $\alpha$.

The best fit shown by the solid line in Fig. 2(a) was obtained with $n=2$ $\mu$m$^{-2}$ per nanotube layer and $R_{\text{ratio}}=100$. The extracted density value is consistent with the density of nanotubes estimated from AFM images of the nanotube films used in the experimental work.$^{23}$ The error bar on the nanotube density $n$ extracted using the fitting procedure is ±15%. The extracted value for the resistance ratio can also be compared to estimates from previous work. In particular, it has been shown by several experiments that the tube-tube junction resistance is larger than the resistance of the nanotubes themselves by a factor of around 30–70 for SS and MM junctions and by a factor of at least an order of magnitude higher than that for MS junctions.$^{26}$ Since MS junctions are more resistive, they do not contribute to conduction as much as SS and MM junctions do. As a result, $R_{\text{ratio}}$, defined in Eq. (2) is expected to be higher than but close to the range 30–70 observed for SS and MM junctions. The value of $R_{\text{ratio}}=100$ we have extracted using the fitting procedure is

$$
R_{\text{ratio}} = \frac{R_{\text{JCT}}}{R_0}.
$$

FIG. 2. (Color online) (a) Log-log plot of normalized nanotube film resistivity versus device width. The individual data points are the experimental results from our previous work (Ref. 23) for a nanotube film with device length $L=7$, 50, or 200 $\mu$m (labeled by different symbols) and average thickness $t=15$ nm. The solid line represents the simulation best fit to the experimental data with $R_{\text{ratio}}=100$ and $n=2$ $\mu$m$^{-2}$. The other simulation parameters are $L=7$ $\mu$m, $l_{\text{CNT}}=2$ $\mu$m, and $t=15$ nm. (b) Log-log plot of normalized resistivity versus device length $L$ for three different nanotube densities $n$, as labeled by different symbols in the plot, calculated using our simulation code for a device with $W=2$ $\mu$m.
consistent with these observations. The experimentally observed value of \( \alpha \) could still be matched by the simulation even when \( R_{\text{ratio}} \) was changed by \( \pm 50\% \), putting a bound on the sensitivity of the \( \alpha \) fit to the value of \( R_{\text{ratio}} \).

It is clear from Fig. 2(a) that the simulation results agree well with the experimental data. However, the decrease in resistivity for widths above 2 \( \mu \text{m} \) observed experimentally (although not as strong as below \( W<2 \mu \text{m} \)) is not captured by the simulations. This discrepancy can be explained by the presence of some nanotubes much longer than 2 \( \mu \text{m} \) in the experimental nanotube films, whereas in the simulations all nanotubes were assumed to have a fixed length \( l_{\text{CNT}}=2 \mu \text{m} \). As we will show explicitly later, when \( l_{\text{CNT}} \) increases, \( W_C \) moves to higher widths. As a result, the decrease in resistivity observed experimentally is consistent with the existence of some much longer nanotubes in the film. Furthermore, experiments on thicker films have shown that, even in the presence of some longer nanotubes, the resistivity eventually saturates for device widths above 20 \( \mu \text{m} \).\(^{23}\)

It can also be seen from the experimental data in Fig. 2(a) that for longer devices, the inverse power-law behavior seems to hold up to a wider device width. This can be explained by the fact that for longer devices, there is a higher probability that some conduction paths are eliminated sooner as the device width shrinks, resulting in a larger critical width \( W_C \). However, the number of experimental data points is too few for a conclusive fit for each separate length, and the simulation time becomes prohibitively long for device lengths above approximately 10 \( \mu \text{m} \). Due to these limitations, we have chosen to use the smallest length device (\( L =7 \mu \text{m} \)) for our simulations and fit all the experimental data points with a single inverse power-law curve. Although this is an approximation, it can still capture the essential physics of the experimentally observed resistivity scaling in single-walled nanotube films.

Figure 2(b) illustrates normalized resistivity versus device length \( L \) for three different nanotube densities calculated using our simulation code for a device with \( W=2 \mu \text{m} \). All other simulation parameters are the same as those in Fig. 2(a). Unless otherwise mentioned, the same device and nanotube parameters will be used in the remainder of the paper. It is evident from Fig. 2(b) that the resistivity starts to decrease from its maximum constant value when the device length \( L \) becomes smaller, in agreement with previous experimental and theoretical results.\(^{2,24}\) At large \( L \), each conduction path consists of many nanotubes in series, and total length and number of junctions of each conduction path vary linearly with the device length. As a result, the total film resistivity also varies linearly with \( L \) and the film behaves like a homogeneous material with a constant resistivity. On the other hand, when \( L \) becomes comparable to the nanotube length, the statistical distribution of nanotubes in the film can result in short conduction paths consisting of only a few nanotubes connecting source to drain, decreasing the total resistance of the film. Figure 2(b) shows that the effect of \( L \) on resistivity is more pronounced when the nanotube density is lower. This is because if the nanotube density is low, the number of conduction paths between source and drain decreases drastically as the device length increases, which increases the resistivity more strongly. This effect has also been observed in previous theoretical and experimental work.\(^{4,24}\)

In addition to matching the experimental data, we have also used numerical simulations to systematically study the effects of four parameters: namely, resistance ratio, nanotube density, nanotube length, and nanotube alignment on the CNT film resistivity and its scaling with device width.

### A. Effect of resistance ratio

Figure 3 shows the normalized resistivity versus device width for \( R_{\text{ratio}} \) ranging from \( 10^{-2} \) to \( 10^4 \). It is evident from Fig. 3 that increasing \( R_{\text{ratio}} \) increases the critical exponent \( \alpha \), but does not have a significant effect on the critical width \( W_C \), since \( W_C \) is only determined by nanotube density and geometrical parameters. In particular, \( \alpha \) increases from 0.52 to 1.95 when \( R_{\text{ratio}} \) changes from \( 10^{-2} \) to \( 10^4 \). When \( R_{\text{ratio}} \) is very low, nanotubes form low-resistance contacts with each other and the film resistivity depends mainly on the total length of the conduction paths. On the other hand, when \( R_{\text{ratio}} \) is very high, the film resistivity mainly depends on the number of contacts in the conduction paths. When the device width is reduced, the number of tube-tube junctions in the remaining conduction paths increases significantly due to the random angular distribution of the remaining nanotube segments, whereas the lengths of the remaining conduction paths do not increase that strongly. As a result, increasing \( R_{\text{ratio}} \) results in a larger value of the critical exponent \( \alpha \).

To illustrate this point further, the inset of Fig. 3 depicts \( \alpha \) as a function of \( R_{\text{ratio}} \). In the nanotube resistance-limited transport regime, \( \alpha \) is constant at a value of about 0.5. It starts to increase as the resistance ratio increases above 1 and finally saturates at a value of around 2 in the junction resistance-limited transport regime. Since \( \alpha \) also depends on several other parameters, such as nanotube density, length, and alignment, the lowest and highest values obtained from the inset of Fig. 3 do not give the absolute limits on \( \alpha \).
increased number of paths per width for dense films, width scaling effects become visible only at smaller widths, which results in a smaller value of the critical exponent \(\alpha\) for smaller nanotube density. At higher densities, the transition starts at smaller widths, which indicates a smaller \(W_C\), but the transition slope is steeper, which indicates a higher value of \(\alpha\).

In the inset of Fig. 4(b), the percolation probability \(P\) versus width is plotted for a device with \(L=4\ \mu m\) and \(W=4\ \mu m\). It is evident from this figure that as \(n\) increases, the critical width \(W_C\) shifts to lower widths. At higher densities, there are more conduction paths which have narrower width distributions. As a result, the resistivity decreases as the number of conducting paths decreases and the average path length between source and drain decreases, both of which reduce the film resistivity. Furthermore, the rate of change of resistivity decreases at high density values, since adding more nanotubes to an already dense film is less likely to introduce a significant number of new conduction paths or reduce the length and the number of junctions in existing paths.

C. Effect of nanotube length

It is clear from Figs. 2(a) and 2(b) that the device geometry-dependent resistivity scaling behavior in nanotube films is observed when the device length or width becomes comparable to the length of individual nanotubes making up the film. Figure 5(a) shows normalized resistivity versus device width for three different nanotube lengths ranging from \(l_{CNT}=1.5\) to \(4\ \mu m\), for a device with \(L=4\ \mu m\). It is evident from this figure that as \(l_{CNT}\) increases, the critical width \(W_C\) moves to higher widths and the critical exponent increases. For tube-tube junction resistance-limited transport (i.e., high \(R_{nano}\), when \(l_{CNT}\) is longer, the conduction paths have a wider width distribution. Therefore, as \(W\) is decreased, the conduction paths start to get disconnected at higher values of \(W_C\). Furthermore, due to the increased number of paths per width removed from the film because of the higher nanotube density, the resistivity starts to increase at a smaller \(W_C\), but the rate of power law increase is much faster.

Figure 4(b) depicts these trends from a different point of view by plotting the percolation probability \(P\), defined earlier, versus width for different densities ranging from 1 to 3 \(\mu m^{-2}\). For all densities, the probability of having a conduction path goes from 1 at large widths to 0 at very small widths. However, as the width decreases, the percolation probability transition profile from 1 to 0 is quite different for different densities. At higher densities, the transition starts at smaller widths, which indicates a smaller \(W_C\), but the transition slope is steeper, which indicates a higher value of \(\alpha\).

For a general 3D percolation problem, it has been shown that near the percolation threshold, the resistivity exhibits an inverse power law dependence on density given by

\[
\rho \propto (n - n_c)^{-\beta},
\]

where \(n_c\) is the critical density at the percolation threshold and \(\beta\) is the critical exponent for density.\(^{30}\) We have also studied this dependence as shown in the inset of Fig. 4(b), where normalized resistivity versus density is plotted for a device with \(L=4\ \mu m\) and \(W=4\ \mu m\). It is evident from this inset that the resistivity as a function of density obeys Eq. (4) near the percolation threshold with a critical exponent \(\beta = 2.5\) extracted from the simulation data. When more nanotubes are added to the film, the number of conducting paths increases and the average path length between source and drain decreases, both of which reduce the film resistivity. Furthermore, the rate of change of resistivity decreases at high density values, since adding more nanotubes to an already dense film is less likely to introduce a significant number of new conduction paths or reduce the length and the number of junctions in existing paths.
density is kept constant (at a value of 2 \( \mu m^{-2} \)), the resistivity increases sharply as \( l_{CNT} \) decreases. Nanotubes with shorter lengths have a lower chance to make junctions and form a continuous path between source and drain, which results in a higher resistivity. Below a critical nanotube length, this strong resistivity scaling with \( l_{CNT} \) can be fit by an inverse power law of the form \( \rho \propto l_{CNT}^{-\alpha} \), where \( \alpha = 2 \) is the critical exponent for nanotube length scaling extracted from the simulation data. In the second case, the resistivity versus nanotube length is plotted when the density–nanotube-length product is kept constant. Physically, this corresponds to the case when the net weight of the nanotubes vacuum filtered to form the film is kept constant while the nanotubes are cut into smaller lengths. Figure 5(b) shows that the resistivity still increases with decreasing nanotube length in this case, but with a critical exponent of 2.5, which is less than the previous case. Although the increase in nanotube density in this case decreases the resistivity as explained previously, it is not enough to compensate for the increase in resistivity due to the decrease in \( l_{CNT} \). In the third case, the product of density and the square of the nanotube length (i.e., \( n l_{CNT}^2 \)) is kept constant. In this case, the resistivity remains almost constant, which indicates that the resistivity increase due to reduced \( l_{CNT} \) is balanced by the resistivity decrease due to higher \( n \). As a result, the resistivity dependence on \( l_{CNT} \) and \( n \) near the percolation threshold can be fit by an inverse power law of the form \( \rho \propto (n l_{CNT}^2)^{-\beta} \), where \( \gamma / \beta \approx 2 \). In general, the value of the ratio \( \gamma / \beta \) depends on other device and nanotube parameters, such as \( L \), \( W \), and \( R_{ratio} \).

D. Effect of nanotube alignment

Finally, we study the effect of alignment (i.e., in-plane angular orientation) of nanotubes in the film on the resistivity and its scaling with device width. We define \( \theta_a \) as the “nanotube alignment angle,” which is a measure of the degree of nanotube alignment in the film. Nanotubes in our simulation are generated at random angles \( \theta \) with respect to the horizontal axis in the range \(-\theta_a \leq \theta \leq \theta_a\), where \( 0 \leq \theta_a \leq 90^\circ \). When \( \theta_a=90^\circ \), nanotubes are completely randomly distributed, whereas when \( \theta_a=0^\circ \), they are perfectly aligned. Figure 6 shows normalized resistivity versus width for three different nanotube alignment angles: namely, \( \theta_a=18^\circ \), \( 36^\circ \), and \( 90^\circ \). It
is evident from Fig. 6 that the normalized resistivity $W_C$ and $\alpha$ all change as the nanotubes become more aligned (i.e., $\theta_a$ becomes smaller). The value of $\rho_{\min}$ initially decreases as $\theta_a$ goes from 90° to 36° because aligned nanotubes help to form conduction paths with fewer junctions and shorter lengths between the source and drain electrodes. Surprisingly, however, the resistivity starts to increase when the degree of alignment in the film is increased even further (i.e., when $\theta_a=18^\circ$). In that case, each nanotube forms too few junctions with its neighbors, because nanotubes mostly lie parallel to each other. Therefore, many existing conduction paths are eliminated and resistivity is increased.

Furthermore, it can be seen from Fig. 6 that as the nanotube alignment angle $\theta_a$ decreases, both $W_C$ and $\alpha$ decrease. This is because as the nanotubes become more aligned, the width distributions of conduction paths in the film become narrower. As a result, width scaling becomes visible only at smaller widths, which decreases $W_C$, and relatively fewer conduction paths per width are removed, which decreases $\alpha$. In short, although $\rho_{\min}$ first decreases then increases as $\theta_a$ decreases, $W_C$ and $\alpha$ decrease monotonically with decreasing $\theta_a$.

The inset in Fig. 6 illustrates the effect of alignment on film resistivity. The normalized resistivity versus nanotube alignment angle $\theta_a$ is plotted in this figure for $W=2\ \mu m$. It is evident from this inset that the resistivity slowly decreases as $\theta_a$ is reduced and reaches a minimum value at $\theta_a \sim 45^\circ$. As $\theta_a$ is reduced even further, the resistivity starts to increase. The reason for this behavior is the same as that discussed for $\rho_{\min}$ in Fig. 6. In other words, the resistivity minimum occurs for a partially aligned, rather than perfectly aligned, nanotube film. The location of this resistivity minimum can depend on other device and nanotube parameters, and therefore, should be calculated for each device condition separately.

The inset of Fig. 6 also shows that, at small alignment angles near the percolation threshold, the resistivity exhibits an inverse power-law dependence on $\theta_a$ given by

$$\rho \propto \theta_a^{-\kappa},$$

where $\kappa=2.9$ is the critical exponent for nanotube alignment extracted from the slope of the log-log plot. This strong scaling with $\theta_a$ is due to the fact that as the nanotubes align parallel to each other, many conduction paths are eliminated, which increases the resistivity significantly. These results are in agreement with recent experimental work on the effect of nanotube alignment on percolation conductivity in carbon nanotube/polymer composites.22

Our simulation results illustrate clearly that decreasing the device width $W$, decreasing the density $n$, decreasing the nanotube length $l_{CNT}$, and aligning the nanotubes (i.e., decreasing the nanotube alignment angle $\theta_a$) all cause the nanotube film to approach the percolation threshold. Furthermore, near the percolation threshold, the resistivity of the nanotube film exhibits an inverse power-law dependence on all of these parameters. In other words, regardless of how we approach the percolation threshold, we observe an inverse power-law behavior, which is a distinct signature of percolating conduction.

However, the strength of resistivity scaling for each parameter, represented by the corresponding critical exponent, is different. This strength depends on how strongly a particular parameter changes the conduction paths in the film. Furthermore, these parameters are not completely independent. For example, as we have demonstrated explicitly, the strength of resistivity scaling with device width depends on nanotube density, length, and alignment.

IV. CONCLUSIONS

In summary, we have used a Monte Carlo simulation platform to model percolating conduction in single-walled carbon nanotube films. We have demonstrated that this simple model can fit the experimental results on resistivity scaling as a function of device width. In addition, we have demonstrated that geometry-dependent resistivity scaling in single-walled carbon nanotube films depends strongly on nanotube and device parameters. In particular, we have studied the effect of four parameters: namely, resistance ratio, nanotube density, length, and alignment on resistivity and its scaling with device width. Stronger width scaling is observed when the transport in the nanotube film is dominated by the tube-tube contact resistance. Increasing the nanotube density decreases the film resistivity strongly and results in a higher critical exponent $\alpha$ for width scaling and lower critical width $W_C$. Increasing the nanotube length also reduces the film resistivity, but increases both $\alpha$ and $W_C$. In addition, the lowest resistivity occurs for a partially aligned, rather than perfectly aligned, nanotube film. Increasing the degree of alignment reduces both $\alpha$ and $W_C$. We have systematically explained these observations, which are in agreement with previous experimental work, by simple physical and geometrical arguments. We have also observed that, near the percolation threshold, the resistivity of the nanotube film exhibits an inverse power-law dependence on all of these parameters, which is a distinct signature of percolating conduction. However, the strength of resistivity scaling for each parameter, represented by the corresponding critical exponent, is different.

Our simulation results presented here are not limited to carbon nanotubes, but are applicable to a broader range of problems involving percolating transport in networks, composites, or films made up of one-dimensional conductors, such as nanowires and nanorods. Monte Carlo simulations, as presented in this paper, can help elucidate the effects of various parameters on percolating transport mechanisms in films made up of one-dimensional conductors. This would be an essential step towards understanding and characterizing the performance of these nanomaterials in electronic and optoelectronic devices.

ACKNOWLEDGMENTS

The authors would like to thank Jing Guo for fruitful discussions. This work was funded by a Southeastern Center for Electrical Engineering Education (SCEEE) junior faculty development award.
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PHYSICAL REVIEW B 75, 125432 (2007)

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2J. Liu, S. Fan, and H. Dai, MRS Bull. 29, 244 (2004).


