

# 2-D ELECTRIC FIELD ASSISTED ASSEMBLY OF SINGLE CARBON NANOTUBES AND THE EFFECT ON THE APPLIED FIELD

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## ABSTRACT

This paper reports on research work on electric field assisted assembly of single carbon nanotubes onto micro-circuit electrodes, and the effect of the carbon nanotubes on the electric field. The research supports the development of nanoelectronics for reducing weight in military systems. A simulation method of assembly processes of carbon nanotubes by dielectrophoresis is introduced. The method considers the effect of carbon nanotubes on the electric field. A calculation model of the dielectrophoretic force based on the effective dipole moment method is presented. The model divides a carbon nanotube into multiple segments, computes the dielectrophoretic force for each segment and sums all of the forces to get a total effect. Compared to the field non-uniformity around the whole carbon nanotube, the field non-uniformity around each segment is reduced, leading to increased computational accuracy. The method can be used to simulate the dielectrophoretic assembly processes of a carbon nanotube originally located at any position of the electric field and the numerical results help to analyze carbon nanotube assembly processes and to optimize the process controlling parameters.

## 1. INTRODUCTION

The excellent electrical, mechanical, and thermal properties of carbon nanotubes (CNTs) make them suitable for nanoelectronics connections. One requirement is the need to align and deposit single or multiple CNTs between electronic conductors. Among the present manipulation methods, alternating current (AC) electric field assisted assembly of CNTs has attracted much research [Chen et al., 2004; Boote and Evans, 2005; Li et al., 2005; Han et al., 2006]. A drop of dielectric liquid medium containing CNTs is deposited onto an electrode region on a substrate. In the presence of an externally applied AC field, the polarized CNTs align themselves immediately to the field and, when the polarizability of the CNTs is greater than that of the medium, move towards the high field region, i.e., the gap between the electrodes, finally depositing and bridging the gap by means of dielectrophoresis (DEP) (Fig. 1). The direction

of the force and therefore the motion of the CNTs remain the same upon field reversal in an AC field of adequately high frequency, because the induced dipole on the CNTs will be inverted as well [Morgan and Green, 2003].

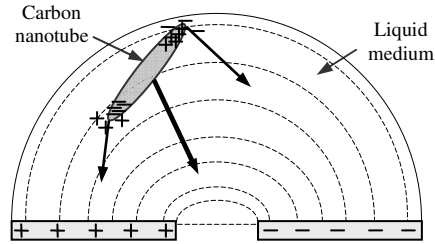


Fig. 1 Schematic of the assembly of CNTs by DEP

The variables influencing an assembly process of CNTs by DEP include the electrode geometry, the magnitude and frequency of the AC source, the electrical properties of the CNTs and liquid medium, the concentration of CNTs in the medium, and the time duration of the electric field. A set of feasible assembly parameters is important for an assembly process where the deposition of a small number of CNTs is required. Process simulation provides a method to investigate and determine these parameters.

Present DEP force models and force calculations have assumed that a CNT in an externally applied electric field does not disturb the field. Our simulation work, however, reveals that a CNT may have a significant influence on the field gradient. Fig. 2 shows field simulation results by COMSOL Multiphysics 3.2 [COMSOL Company, 2005]. The metallic CNT alters the field potential and field lines, and leads to a field concentration at both ends of the CNT. Therefore, the CNT will change the alignment and deposition force, and affect the assembly process and assembly results. Dimaki and Bøggild [Dimaki and Bøggild, 2004] numerically studied CNT trapping and separation processes by DEP, drag force and Brownian motion, and suggested that relatively low frequencies such as 1 MHz may be optimal for separation of semiconducting and metallic nanotubes. Kim and Han [Kim and Han, 2005] simulated CNT assembly processes to fabricate an atomic force microscope tip, and found that the optimal distance

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between the tip and the electrode was 10  $\mu\text{m}$ . FEMLAB was used to simulate the electric field but the effect of a CNT on the field was not considered in both studies.

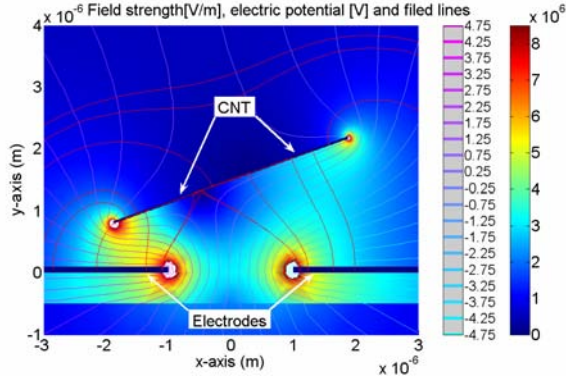


Fig. 2 A CNT present in an electric field alters the field potential, the field lines and the field strength

Among the two methods to calculate the DEP force and torque, the effective dipole moment method is used in this research because it avoids integration which has to be carried out in the Maxwell stress tensor method. The effective dipole moment method computes the force and torque exerted on a particle based on the induced effective dipole moment. The method is only valid when the electric field is uniform or slightly non-uniform, as long as its non-uniformity is negligible around the particle, an assumption referred to as the dipole approximation [Morgan and Green, 2003]. In the case of micro- or nano-electronics connections, the length of a CNT for assembly is greater than the gap between the two electrode tips. When such a CNT is located close to the electrode gap or when the effect of a CNT on the field is considered, the classical effective dipole moment method is no longer valid due to the non-uniformity of the electric field in the vicinity of the CNT, which leads to a considerable field strength change along the CNT as shown in Fig. 2.

This paper presents a two-dimensional DEP field simulation of a CNT assembly considering the effect of the CNT on the DEP field. COMSOL Multiphysics 3.2 [COMSOL Company, 2005] is used to dynamically generate the required field information around the CNT. Because the effective dipole moment method is no longer valid under the conditions of this study, the dipole length had to be shortened to maintain the dipole approximation. Our method is to divide a CNT into segments along its length. Compared to the field non-uniformity along the whole CNT, the field non-uniformity along each segment is greatly reduced. The DEP force for each segment can be calculated based on the local electric field using the effective dipole moment method, and then all of the DEP forces are summed to obtain a total effect. A comparison of the arrival time of a CNT with and without its influence on the field will be subsequently shown.

Experimental research is being carried out based on the numerical results. The objective is to assemble metallic CNTs in patterns shown in Fig.3, which are commonly used in the present integrated circuit (IC) chips. To fulfill real-time monitoring of an assembly process, a time-varying impedance model of the electrode gap has been developed to evaluate the number of CNTs which span the gap by measuring the variation of gap impedance during the assembly process. We will also measure the resistance and current-voltage ( $I$ - $V$ ) characteristics of assembled CNTs to evaluate the electrical properties of deposited CNTs and the assembly quality. We will report the results in the near future.

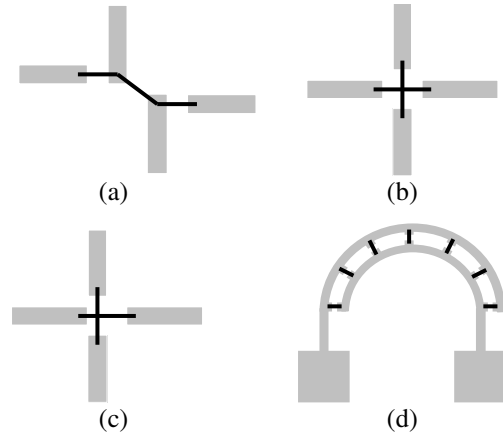


Fig. 3 Electrode patterns for (a) parallel, (b) cross, (c) T interconnects, (d) interconnects for a multiplexer switch

## 2. MODEL AND METHOD FOR THE DEP CALCULATIONS

In a CNT assembly process where CNTs are required to span an electrode gap, the length of the CNTs is greater than the gap distance. When such a CNT is located close to the electrode gap or when the effect of a CNT on the field is considered, the classical effective dipole moment method is no longer valid and the non-uniformity of the electric field along the CNT must be considered. Our method is to divide the length of the CNT into multiple segments to maintain the dipole approximation over each segment. When a CNT is polarized in a dielectric liquid under an AC electric field and aligned with the electric field, the induced charges distribute mainly along the interface near the two ends of the CNT. The electric field around the two ends of the CNT is more non-uniform than that along the center part of the CNT. This requires a finer division of the CNT near the two ends to maintain the dipole approximation. Therefore, we present a combined model to calculate the DEP force as shown in Fig. 4. The model consists of cylindrical segments located in the center portion of the CNT and several spherical segments at each end of the CNT. Numerical error due to the volume change from cylinders to spheres is negligible

because the sharp change of field strength as shown in Fig. 2 takes place only at the ends of the CNT and several spheres are enough to maintain the dipole approximation.



Fig. 4 A combined model comprised of cylinders and spheres

If we divide the CNT into  $N_1$  cylinders and  $N_2$  ( $N_2$  is an even number) spheres with  $N_2/2$  spheres at each end of the CNT, then the total segment number is  $N = N_1 + N_2$ . If  $\vec{F}_i$  indicates the DEP force on the  $i$ th CNT segment (cylinder or sphere) as illustrated in Fig. 5(a), and the DEP forces for the  $k$ th cylinder and the  $l$ th sphere are  $\vec{F}_k$  and  $\vec{F}_l$ , respectively, then the total DEP force of the CNT is

$$\vec{F}_{DEP} = \sum_{i=1}^N \vec{F}_i = \sum_{k=1}^{N_1} \vec{F}_k + \sum_{l=1}^{N_2} \vec{F}_l. \quad (1)$$

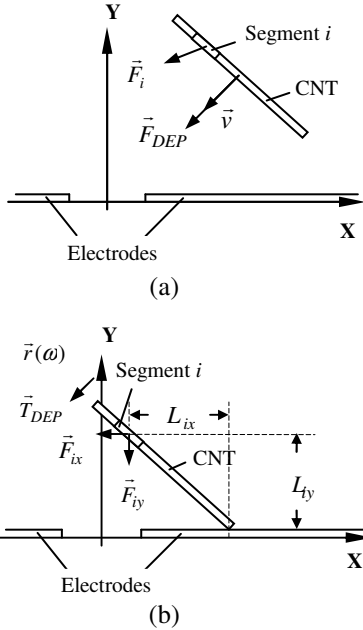


Fig. 5 (a) Translation and (b) rotation of the CNT in the given coordinate system

If the radius of the CNT is  $r$  and the length of the  $k$ th cylinder is  $l_k$ , the volume of the cylinder is  $V_k = \pi r^2 l_k$ . When the CNT is aligned with the field line, the planar DEP force exerted on the  $k$ th cylinder is [Chan et al., 2004],

$$\vec{F}_k = \frac{\pi r^2 l_k}{4} \epsilon_m \text{Re} \left[ \frac{\tilde{\epsilon}_p - \tilde{\epsilon}_m}{\tilde{\epsilon}_m + (\tilde{\epsilon}_p - \tilde{\epsilon}_m) L_{//}} \right] \nabla |\vec{E}_k|^2. \quad (2)$$

$\vec{E}_k$  is the local electric field for the  $k$ th cylinder. The local field strength is evaluated for the center point of each cylinder based on the field simulation.  $\text{Re}$  means to take the real part of a complex number.  $\tilde{\epsilon}_p$  and  $\tilde{\epsilon}_m$  are respectively the complex permittivity of the CNT and the medium.  $\tilde{\epsilon}_p = \epsilon_p - j\sigma_p / \omega$ ,  $\tilde{\epsilon}_m = \epsilon_m - j\sigma_m / \omega$ .  $\epsilon_p$  and  $\epsilon_m$  are respectively the permittivity of the CNT and the medium,  $\sigma_p$  and  $\sigma_m$  are respectively the conductivity of the CNT and the medium,  $j = \sqrt{-1}$  and  $\omega$  is the angular frequency of the applied AC electric field. The segment depolarization factor of a cylinder is  $L_{//} = (4r^2 / l_k^2) [\ln(l_k / r) - 1]$ . The DEP force exerted on the  $l$ th sphere is [Morgan and Green, 2003]

$$\vec{F}_l = \pi \epsilon_m r^3 \text{Re} \left[ \frac{\tilde{\epsilon}_p - \tilde{\epsilon}_m}{\tilde{\epsilon}_p + 2\tilde{\epsilon}_m} \right] \nabla |\vec{E}_l|^2, \quad (3)$$

where  $\vec{E}_l$  is the local field strength for the  $l$ th sphere. The local field strength is evaluated for the center point of each sphere based on the field simulation.

When a CNT moves in a liquid medium, considering the effect of the medium, the translational velocity of the CNT may be limited by its terminal velocity

$\vec{v} = \frac{\vec{F}_{DEP}}{f} \left( 1 - e^{-\frac{f}{m}t} \right)$  [Morgan and Green, 2003].  $f$  is the friction factor for a CNT moving sideways and is given

by  $f = \frac{8\pi\eta L}{2 \ln(L/r) - 1}$ , where  $\eta$  is the viscosity of the

liquid,  $m$  is the mass of the CNT, and  $L$  is the total length of the CNT. Because the CNT translational times are much greater than the terminal velocity characteristic

time constant,  $\tau_a = \frac{m}{f}$ , which is of order  $10^{-10}$  s in our

case, the CNT is assumed to always move with the terminal velocity, so

$$\vec{v} = \frac{\vec{F}_{DEP}}{f}. \quad (4)$$

It has been reported that a CNT under the DEP will be very quickly aligned to the applied field direction and then will more slowly translate [Asokan et al., 2003; Li et al., 2005]. Based on our calculations, a typical rotational time for 30 degrees is less than  $10^{-3}$  s, much less than a typical translational time which is several seconds. Therefore, we assume that a CNT in the electric field first aligns to the field direction immediately after the field is applied, and then translates under the DEP force. The translational velocity of the CNT is determined by Equation (4). The CNT slightly adjusts its orientation in a continuous way to the applied field during the translation.

When the CNT finally touches the electrodes at one end, we assume that end of the CNT sticks at the contact point due to the Van der Waals Forces [Hertel et al., 1998], and then rotates about the touching point. Using Equations (2) and (3), the X and Y components of the DEP force for each segment can be calculated. Then the magnitude of the torque from each segment, according to Fig. 5(b), is

$$T_i = F_{ix}L_{iy} + F_{iy}L_{ix}, \quad (5)$$

and the total torque is

$$\vec{T}_{DEP} = \sum_{i=1}^N \vec{T}_i. \quad (6)$$

The rotational rate of the CNT under the DEP torque  $\vec{T}_{DEP}$  is [Morgan and Green, 2003]

$$\vec{\tau}(\omega) = \frac{\vec{T}_{DEP}}{f_\theta}, \quad (7)$$

where  $f_\theta$  is the rotational friction factor, and

$$f_\theta = \frac{16\pi\eta r^3(K^4 - 1)}{3 \left[ \frac{2K^2 - 1}{\sqrt{K^2 - 1}} \ln(K + \sqrt{K^2 - 1}) - K \right]}, \quad \text{where } K = \frac{L}{2r}$$

is the aspect ratio of the CNT [Happel and Brenner, 1973]. The CNT rotates about the contact point as shown in Fig. 5(b) at a rotational speed determined by Equation (7), until it orients along the x-axis.

The effect of Brownian motion on the movement of a CNT in an AC field has been studied and the effect of thermal energy is negligible if the amplitude of the electric field is greater than an order of  $10^3$  V/m [Kim and Han, 2005]. In our case, the typical electric field is of order  $10^5$  V/m. Therefore, Brownian motion is not considered in our studies. We estimated that the mass of a multi-walled CNT with a length of  $4 \mu\text{m}$  and a diameter of  $40 \text{ nm}$  is  $1.1 \times 10^{-17} \text{ kg}$  based on the density of graphite. Our typical DEP force is of order  $\sim 10^{-10} \text{ N}$ , depending on the distance of the CNT from the electrode gap. Therefore, gravity is also ignored in this study since the CNT weight is 6 orders of magnitude smaller than the DEP force.

### 3. SIMULATION

COMSOL Multiphysics [COMSOL Company, 2005] provides a tool for modeling and solving problems based on partial differential equations. The Generalized Electrostatics Application Mode in the Electromagnetics Module was used to solve Poisson's equation to compute the required electric field in our CNT assembly system, which contains both dielectric and conductive materials.

The mode adds Gauss' law,  $-\nabla \cdot (\epsilon_0 \epsilon_r \nabla V) = \rho$ , into the continuity equation,  $-\nabla \cdot (\sigma \nabla V) = -\frac{\partial \rho}{\partial t}$ , and for quasi-static cases  $\frac{\partial \rho}{\partial t} \approx \frac{\rho - \rho_0}{T}$ . Here,  $\epsilon_0 = 8.854 \times 10^{-12} \text{ F/m}$ ,  $\epsilon_r$  is the relative permittivity,  $V$  is the potential,  $\rho$  is the volume charge density in  $\text{C/m}^3$ , and  $\rho_0$  is the space charge density at  $t = 0$ , and is assumed zero in this case. This couples conducting and nonconducting media and gives the resulting partial differential equation,  $-\nabla \cdot ((\sigma + \epsilon_0 \epsilon_r / T) \nabla V) = 0$ . Choosing  $T = 8.85 \times 10^{-13}$  seconds, which is 100 times larger than the charge relaxation time of the metallic CNTs, the electric scalar potential  $V$  is obtained and is independent of  $T$ . The electric field  $\vec{E}$  is defined as  $\vec{E} = -\nabla V$ .

Fig. 6 shows a suspension of isopropyl alcohol (IPA) containing CNTs. The droplet was introduced onto a pair of thin film parallel aluminum electrodes deposited on a silicon/silicon dioxide wafer. The dimensions and electrical properties of the CNT assembly system are given below. The hemisphere IPA drop: radius =  $200 \mu\text{m}$ , relative permittivity  $\epsilon_r = 18.6$ , conductivity  $\sigma = 6 \times 10^{-6} \text{ S/m}$ . The metallic multi-walled CNTs: length =  $4 \mu\text{m}$ , radius =  $20 \text{ nm}$ ,  $\epsilon_r = 1 \times 10^4$  [Dimaki and Bøggild, 2004],  $\sigma = 1 \times 10^7 \text{ S/m}$  [Ebbesen et al., 1996]. The Al electrodes: thickness =  $100 \text{ nm}$ , gap =  $2 \mu\text{m}$ , quasi-static potential of the left electrode =  $5 \text{ V}$ , potential of the right electrode =  $-5 \text{ V}$ . The silicon dioxide layer: thickness =  $0.5 \mu\text{m}$ ,  $\epsilon_r = 3.8$ ,  $\sigma = 1 \times 10^{-18} \text{ S/m}$ . The silicon substrate: thickness =  $200 \mu\text{m}$ ,  $\epsilon_r = 11.7$ ,  $\sigma = 1.2 \times 10^{-6} \text{ S/m}$ . The frequency of the applied electric field is  $100 \text{ kHz}$ .

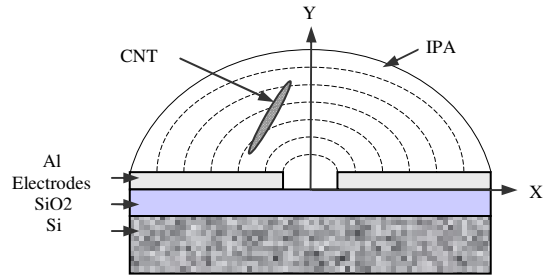


Fig. 6 Schematic of the assembly of CNTs under DEP

The simulation flowchart is shown in Fig. 7. For a CNT at an original position and orientation, we first simulated the electric field without the CNT to find the field direction, and thus the CNT direction, at that position. Then, we simulated the electric field with the CNT to consider the effect of the CNT on the field. Equations (1), (2) and (3) were used to compute the DEP force for each segment and for the entire CNT. The

translational velocity of the CNT was determined with Equation (4). To save computation time, the simulation time steps were based on the distance between the CNT and the electrode gap. Initially, the steps were large and as the CNT approached the electrode gap the time steps were made smaller. When the CNT touched an electrode, we assumed the CNT sticks and rotates around that point at a rotational rate determined by Equation (7), until it orients along the x-axis. The purpose of this simulation was to estimate the arrival time of a CNT at different original positions to determine the assembly process parameters and to eventually monitor the changes in the electrical characteristics of the electrode gap due to CNT deposition.

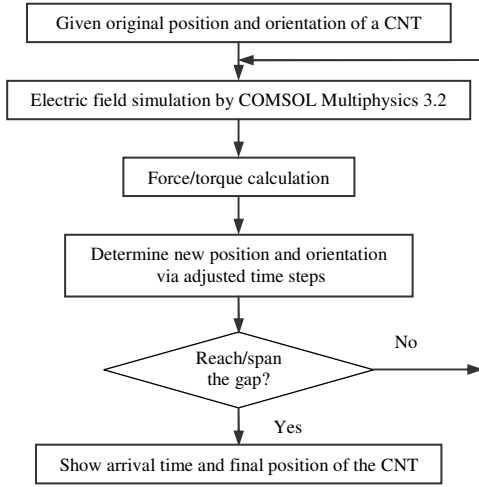


Fig. 7 Flowchart of the simulation process using COMSOL Multiphysics 3.2 and Matlab analysis

Electric field computation is required to calculate the DEP force and torque. When we are considering the effect of a CNT on the field and the field strength of a required segment center point is needed, we can not take the field value of the point directly from a field simulation with the presence of the CNT, because the field strength within a metallic CNT is nearly zero and incorrect field information would be obtained. To properly evaluate the field strength of a required segment center point is important for the DEP calculations. Our method is to take the field values of the four points shown in Fig. 8 to interpolate the required field for the segment center point. Distance  $b$  is selected small enough compared to the diameter of the CNT.

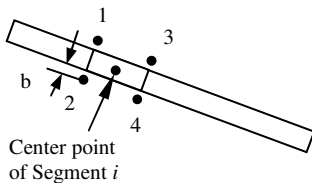


Fig. 8 Interpolation of the required electric field at the center of each segment

## 4. RESULTS

### 4.1. Arrival Time and Trajectories of CNT

We simulated the assembly process of a CNT at multiple original positions and orientations. The global coordinate system was shown in Fig. 5 and 6. Fig. 9(a) shows a CNT in white at its original position  $x_0 = 39.98 \mu\text{m}$ ,  $y_0 = 40 \mu\text{m}$ , and the orientation is  $\theta_0 = 45^\circ$ . The CNT has been widened to make it clearly visible. Fig. 9(b) shows its final assembled position also in white with a considerable scale change. The arrival time of the CNT is 21.50 seconds. From this original position, the CNT just reached the left electrode and bridged the electrode gap after its assembly. To make the images brighter, the color bars in Fig. 9 have been adjusted, so they may not truly indicate the highest overall field strengths. A CNT originally located at  $y_0 = 40 \mu\text{m}$  and  $x_0 > 39.98 \mu\text{m}$  could not reach the left electrode and thus could not span the electrode gap.

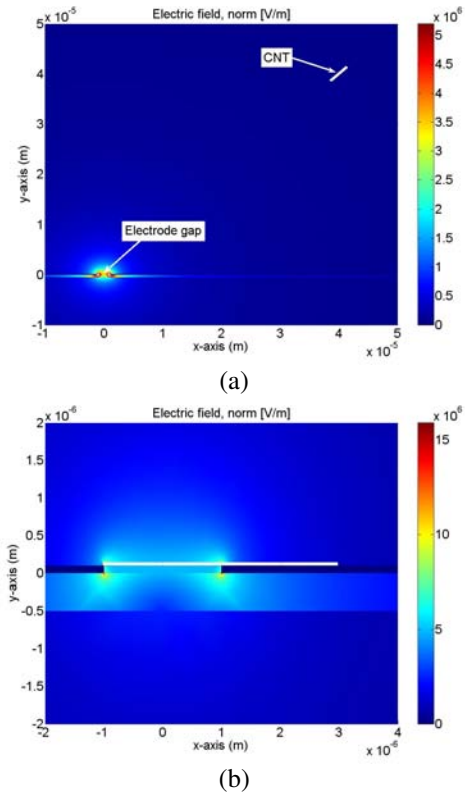


Fig. 9 (a) A CNT originally at  $x_0 = 39.98 \mu\text{m}$ ,  $y_0 = 40 \mu\text{m}$ ,  $\theta_0 = 45^\circ$ , (b) its final assembled position 21.5 s later

The arrival times of a CNT originally at the points (0, 40 $\mu\text{m}$ ), (20 $\mu\text{m}$ , 40 $\mu\text{m}$ ), (39.98 $\mu\text{m}$ , 40 $\mu\text{m}$ ), and (60 $\mu\text{m}$ , 40 $\mu\text{m}$ ) are shown in the second row of Table 1. Fig. 10 shows the center point trajectories of the above CNT assembly processes. Divided by the assembly trajectories

which begin at the point  $(39.98\mu\text{m}, 40\mu\text{m})$  and its symmetrical point with respect to the y-axis  $(-39.98\mu\text{m}, 40\mu\text{m})$ , two regions form, **A** and **B**, as shown in Fig. 11, due to the symmetry of the electric field. In our simulation conditions, a CNT originally located within region **A** will bridge the gap and a CNT in **B** will not.

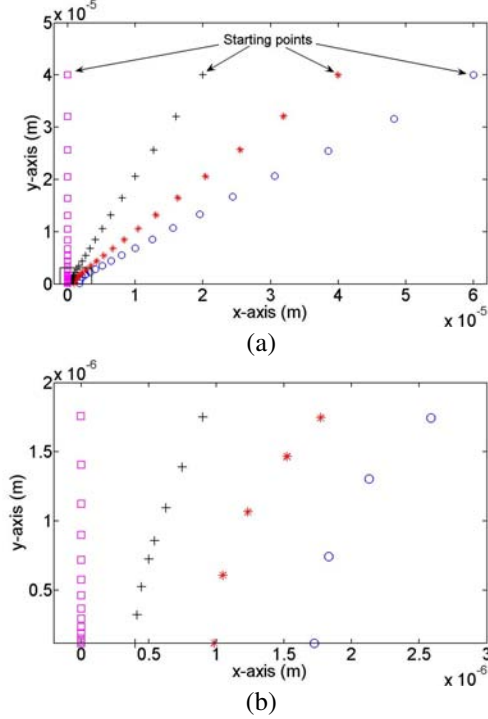


Fig. 10 (a) Trajectories of a CNT originally at different positions, (b) enlarged image of the rectangular region in (a). The purple squares represent the trajectory of a CNT starting from the point  $(0, 40\mu\text{m})$ . The black plus signs indicate the trajectory of a CNT originally located at the point  $(20\mu\text{m}, 40\mu\text{m})$ . The red stars show the trajectory of a CNT which began its assembly from the point  $(39.98\mu\text{m}, 40\mu\text{m})$ . The blue circles give the trajectory of a CNT from the point  $(60\mu\text{m}, 40\mu\text{m})$ .

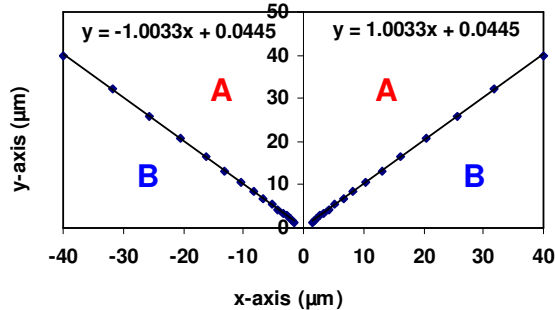


Fig. 11 A CNT originally within region **A** will be assembled to span the electrode gap, and a CNT within **B** will not

When the distance of a CNT from the electrode gap is different, the arrival time of the CNT is also different.

Fig. 12 shows a general relation between the distance of a CNT from the electrode gap and its arrival time. The CNT was assembled originally from the point  $(0, 100\mu\text{m})$  and moved along the y-axis. When the CNT was far from the electrode gap, it moved slowly towards the gap. While the CNT was close to the electrode gap, it translated much faster towards the gap. This result conforms to the finding in Dimaki and Bøggild [Dimaki and Bøggild, 2004] and Kim and Han [Kim and Han, 2005], in spite of the effect of CNT on the electric field was not considered in their work.

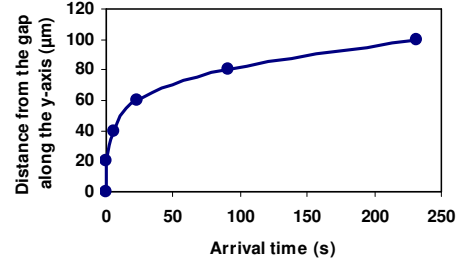


Fig. 12 The relation between CNT initial distance and arrival time

#### 4.2. Effect of a CNT on the Applied Electric Field

To visualize and more closely examine the perturbation of the electric field by a CNT, the electric field strength with the presence of a CNT in the field was computed. The CNT was located with its center at the point  $(5\mu\text{m}, 5\mu\text{m})$  and has been aligned to the field direction which is approximately  $45^\circ$ . The computed field was compared with the field without the presence of the CNT. The results were plotted together in Fig. 13(a) to show the difference between the two cases at one end of the CNT. When considering the perturbation of the CNT on the field, the field strength was greater around the end, and the field was concentrated on the two sharp edges of the end. Inside the CNT, the field was zero because the CNT is metallic. The electric field without considering the effect of the CNT was nearly a plane. Fig. 13(b) shows a cross-sectional plot of Fig. 13(a) along  $y = 6.37\mu\text{m}$ . The field gradient across the CNT determined by points A and B when considering the effect of the CNT on the field, is much larger than that determined by points C and D when without considering the effect. Because the DEP force is proportional to the gradient of  $|\vec{E}|^2$ , a CNT will move much faster when considering its effect on the electric field.

We also simulated the CNT assembly processes without considering the effect of a CNT on the applied field. Table 1 compares the arrival times of a CNT starting at the four points shown in Fig. 10(a), with and without considering its effect on the field. As expected from Fig. 13(b), much longer assembly times were

obtained when without considering the effect of the CNT on the field, compared to those considering the effect.

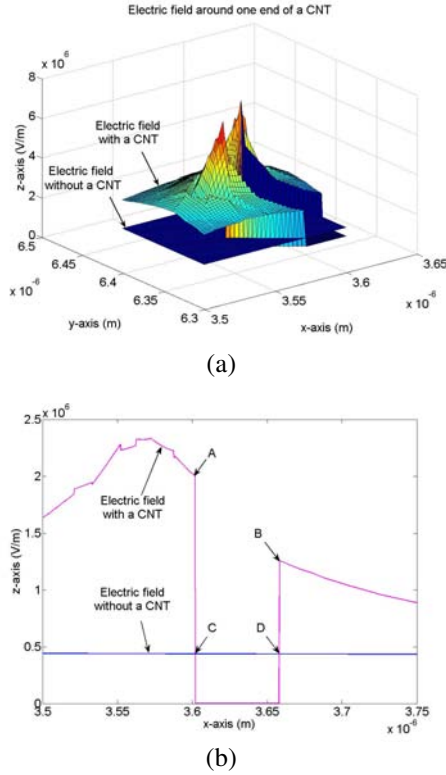


Fig. 13 Electric field around one end of a CNT located at  $x = 5\mu\text{m}$ ,  $y = 5\mu\text{m}$ ,  $\theta_0 = -45^\circ$

Table 1. Comparison of Arrival Times with and without the Effect of a CNT on the Electric Field

Original position ( $\mu\text{m}$ )	(0, 40)	(20, 40)	(39.98, 40)	(60, 40)
Arrival time with the effect (s)	5.97	9.38	21.50	52.73
Arrival time without the effect (s)	311	484	1240	3291

## 5. DISCUSSIONS AND ANALYSIS

Although only one CNT has been considered during an assembly process, our method is applicable to any assembly processes where a small number of CNTs are required to span a pair of electrodes. This is because in such an assembly process the concentration of CNTs in liquid is required to be very low [Chen et al., 2004; Han et al., 2006]. The distance between any two CNTs in liquid is much larger than their physical dimensions. The mutual interact among the CNTs during an assembly is negligible.

Boote and Evans [Boote and Evans, 2005] experimentally studied DEP manipulation of gold nanowires (NWs) using two rounded triangular electrodes at an AC frequency of 150 kHz. They found that the number of randomly deposited NWs on the electrode region strongly depends on the time duration of the electric field, and only some of these deposited NWs bridged the electrode gap. Their findings support our simulation results. Under certain NW concentration, extended time duration permitted a larger range of NWs in the liquid, i.e. more NWs to reach the electrodes as indicated in Fig. 12. That not all deposited NWs bridged the gap justifies our division of regions **A** and **B** in Fig. 11. Chen et al. [Chen et al., 2004] fabricated nanoelectrodes based on controlled placement of CNTs under DEP. The concentration of CNTs in liquid was found to play a crucial role in the spacing of aligned CNTs along the width of their parallel electrodes. The spacing between CNTs was  $2\mu\text{m}$  when the concentration was  $0.04\text{ mg/ml}$ . The spacing was reduced to  $0.2\mu\text{m}$  when the concentration was increased to  $0.4\text{ mg/ml}$ , and the spacing was increased to  $10\mu\text{m}$  when the concentration was reduced to  $0.004\text{ mg/ml}$ . Han et al. [Han et al., 2006] investigated the effect of the concentration on the density of deposited CNTs using multi-walled CNTs.  $0.005\text{ mg/ml}$  was found to be an adequate concentration to assemble the individual CNT when the applied voltage was  $10\text{ V}$  at  $5\text{ MHz}$ . Too many CNTs were deposited at  $0.01\text{ mg/ml}$  and no CNTs were found to bridge the electrode gap at  $0.001\text{ mg/ml}$ . The above experiments conform to our simulation results. On the basis of our simulation, under a certain field time duration and applied voltage, an increased CNT concentration would permit more CNTs to arrive and bridge the electrode gap, thus increasing the density or the number of assembled CNTs and reducing the spacing of CNTs bridging the electrodes.

Based on the above experimental observation, our simulation results can be used to optimize the assembly process parameters to accomplish an assembly where the deposition of a small number of CNTs is required. To span a pair of  $2\mu\text{m}$  wide parallel electrodes with only one CNT under our simulation conditions at the applied voltage of  $10\text{ V}$  peak-to-peak, if the time duration of the electric field is  $5.97\text{ s}$ , according to Table 1, CNTs in region **A** in Figure 11 within  $40\mu\text{m}$  from the electrode gap can reach and bridge the gap, assuming the arrival time of a CNT only depends on its distance and has nothing to do with its direction from the electrode gap. The liquid volume within which CNTs can reach and bridge the gap in region **A** is  $2.512 \times 10^{-9}\text{ ml}$ . A CNT has a mass of  $1.1 \times 10^{-11}\text{ mg}$ . Therefore the concentration of CNTs in liquid should be no more than  $0.0044\text{ mg/ml}$ . Similarly, we calculated the required concentrations for other time duration values shown in Row 2 of Table 1, the relation between the time duration and CNT concentration

was plotted in Fig. 14. If the time duration is increased to 52.73 s, the concentration should be reduced to 0.0013 mg/ml to bridge the electrode gap with only one CNT.

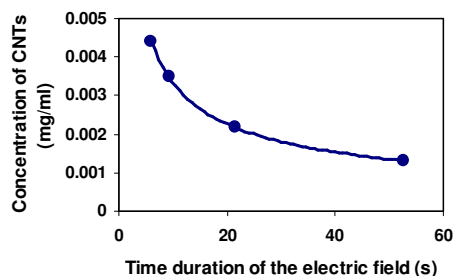


Fig. 14 The relation between the time duration of the field and the concentration of CNTs

## 6. CONCLUSIONS

The study revealed that a CNT in an externally applied electric field affects the field and a simulation method for DEP assembly of CNTs considering this effect was presented. The arrival time of a CNT under the DEP depends on its distance from the electrode gap. The smaller the distance, the faster the CNT moves towards the gap. Both the concentration of CNTs in liquid and the time duration of the electric field affect the number of assembled CNTs. They must be controlled to ensure an assembly of a small number of CNTs. Our simulation provides an effective method to determine a feasible combination of the two parameters. To bridge the electrode gap with only one CNT under our simulation conditions at the applied voltage of 10 V peak-to-peak, the CNT concentration should be no more than 0.0044 mg/ml when the time duration is 5.97 s. When the time duration is increased to 52.73 s, the CNT concentration should be reduced to 0.0013 mg/ml. The research supports the development of nanoelectronics for reducing weight in military systems. This can lead to more miniaturized, stable, durable and portable electronics which can have many benefits to the military.

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