Electrokinetic assembly and manipulation; experimental

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Contents

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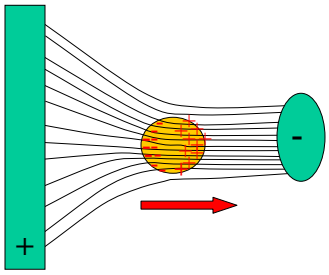
Composite electric field guided assembly

Introduction

- Top-down approaches are limited in functions and fabrication in sub-30 nm length scale.
- Bottom-up approaches are regarded as a fabrication method in the next decades.
- Nanowires as fundamental building blocks for nanoscale devices have been investigated.
  - Field effect transistors (Martel, R., et al., Applied Physics Letters, 1998)
  - Logic circuits (Chen, Z.H., et al., Science, 2006)
  - Electromechanical switches (Kaul, A.B., et al., Nano Letters, 2006)
- Assembly of nanowires is a challenging issue to build molecular devices.

Dielectrophoresis

When a particle is in a non-uniform electric field, it is polarized and thus, dipole moment is generated to transport and orient the particle; dielectrophoresis.



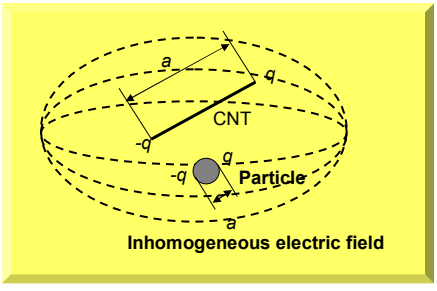
Polarization
Dipole moment
Transport & orientation
Dielectrophoretic force

Dielectrophoretic force

Dielectrophoretic force :

- **Induced by a polarization (induced dipole) in a non-uniform field**
- **CNTs can be attracted.** ***(Chen, et al, Appl. Phys. Lett., 78 2001)***

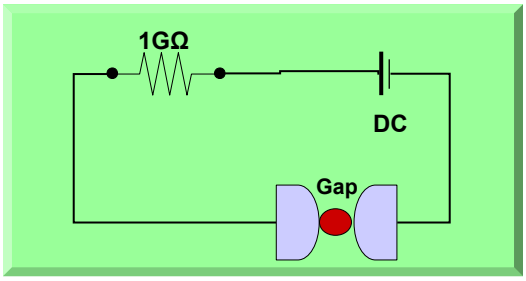
$$F_{DEP} = 2\pi a^3 \varepsilon_m \,\mathrm{Re}\left[\frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* + 2\varepsilon_m^*}\right]\nabla|E|^2$$



Attraction, Filtering & Orientation

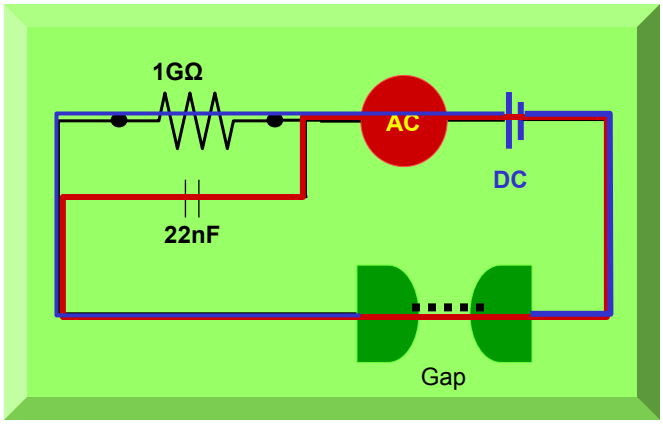
Electrophoretic force

- Electrophoretic force (F_e=qE): electrostatic attraction between charged particles and charged electrodes
- Self-limiting mechanism *(Bezryadin, et al, Appl. Phys. Lett. 71,1997)*



Self-limiting mechanism

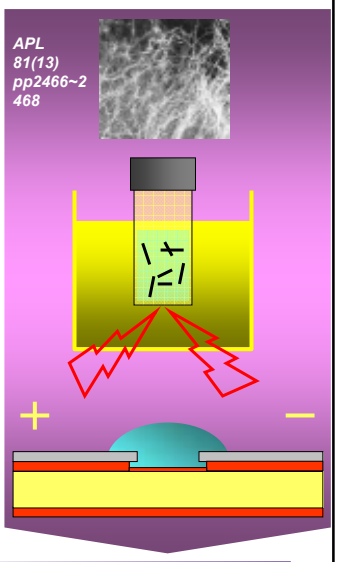
Composite e-field



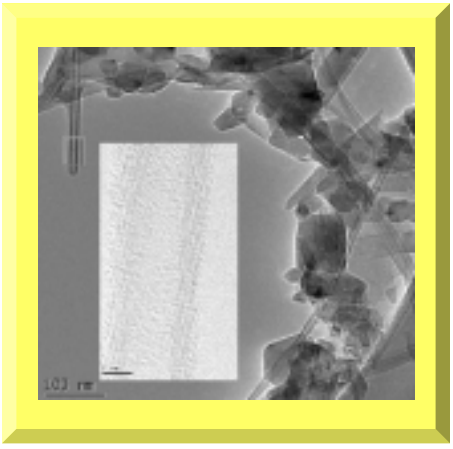
Attraction, Orientation, & Self-limiting mechanism

CNT deposition procedure

- MWCNT source: Arc-discharge method
  - Dilution in ethanol
  - Sonication for 10 hours
  - Individual suspension in the solution
  - A drop of solution (9μl) with an electric field
  - Evaporated at room temperature (~1*min*)
- Electric field: 0.544 V_{rms}/μm
- Frequency: 5MHz



MWCNT source *(APL 81 2466, 2002)*

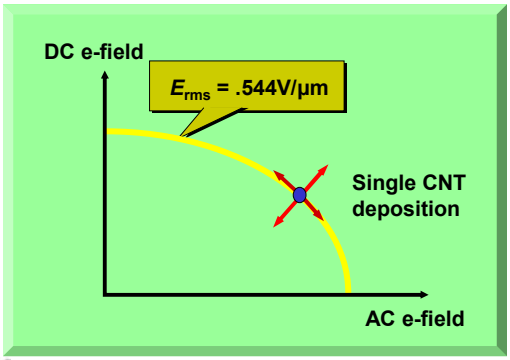


- Crystallized but covered with amorphous carbon
- High electrical resistance due to Schottky barrier and amorphous carbon surface layer

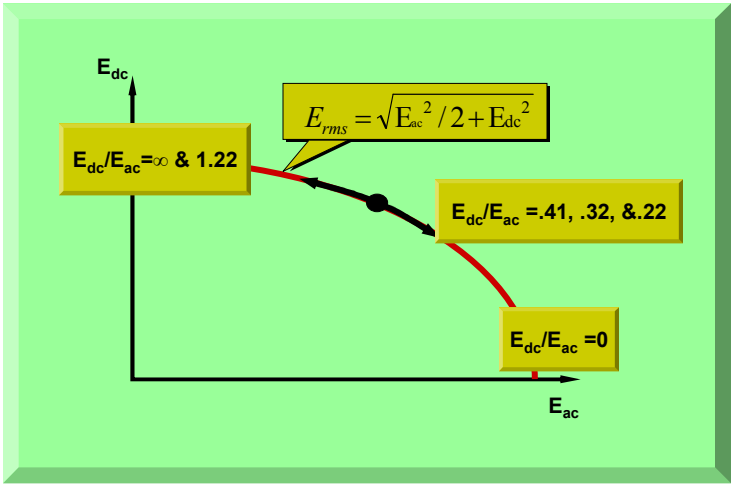
(image by Dr. Xinqi Chen)

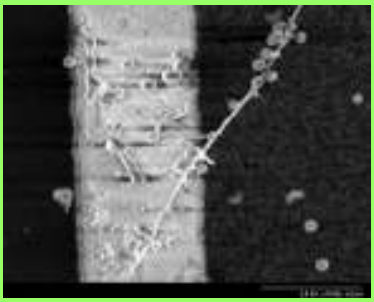
E-field manipulation for a single CNT

- Parameters
  - E-field strength manipulation (.544V/μm)
  - E_{dc}/E_{ac} ratio manipulation

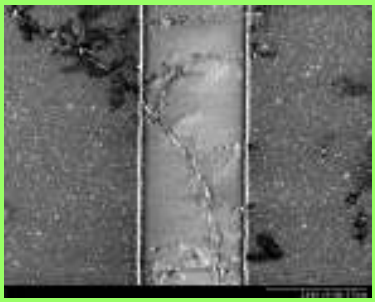


Varying of the E_{dc}/E_{ac} ratio



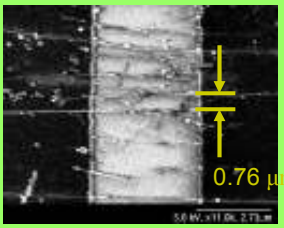


E_{dc}/E_{ac} ratio=∞

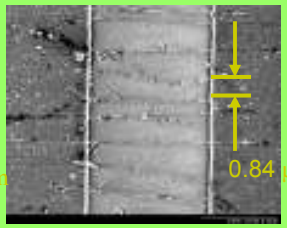


E_{dc}/E_{ac} ratio=1.22

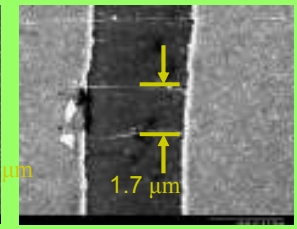
ac electric field (E_{dc}/E_{ac} ratio=0)



(E_{dc}/E_{ac} ratio=0.41)



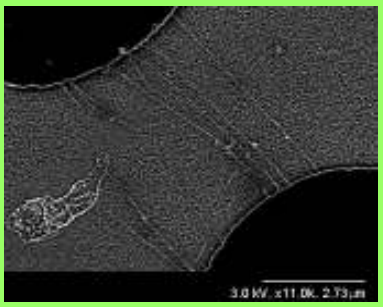
(E_{dc}/E_{ac} ratio=0.32)



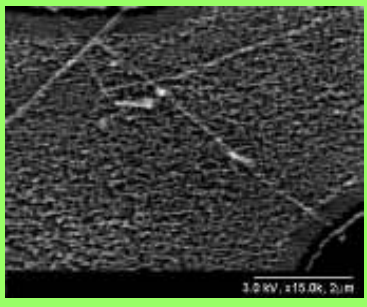
(E_{dc}/E_{ac} ratio=0.22)

Attraction, Orientation, & Periodic pattern

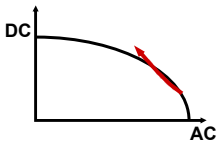
Tuning the deposition



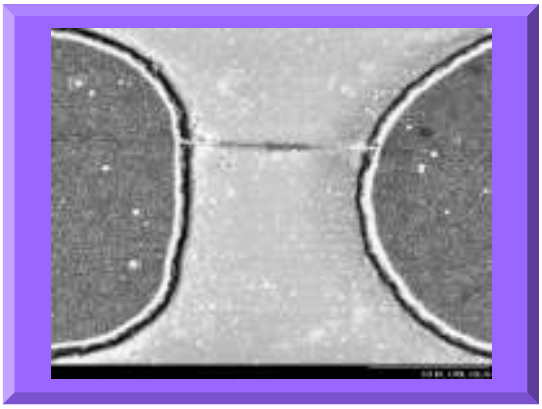
- Multiple deposition (E_{dc}/E_{ac} =0.71)



- Crossing of CNTs (E_{dc}/E_{ac} =0.33)



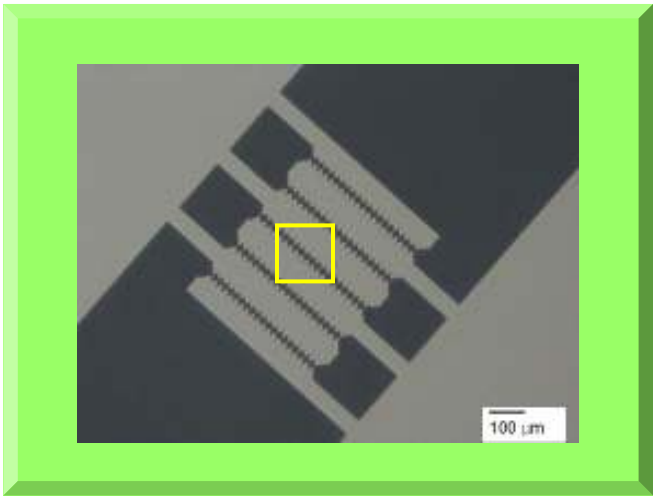
Single MWCNT deposition



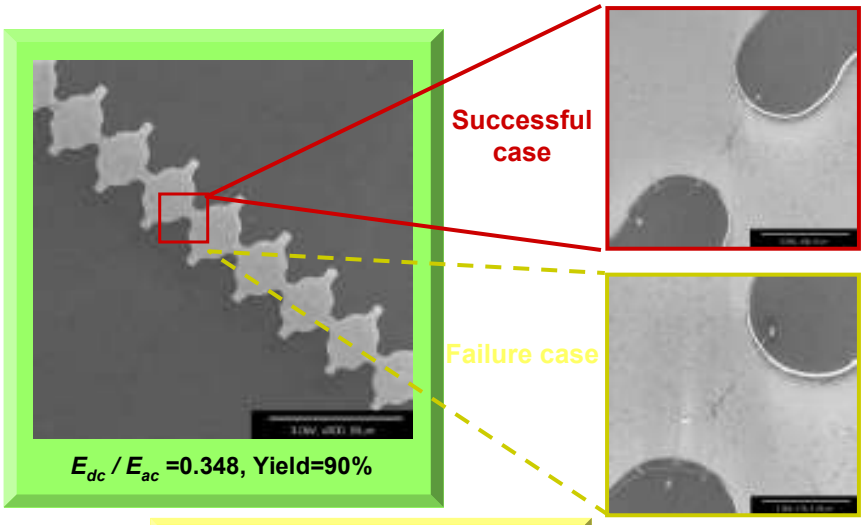
- 3.5μm gap size
- ~20nm dia.
- 7.5μm long
- Spans electrodes
- Few particles
- CEGA

E_{dc}/E_{ac}=0.41 & 0.544V_{rms}/μm @5MHz

Extension to an array with 100 gaps



...100 gaps *(cont'd)*

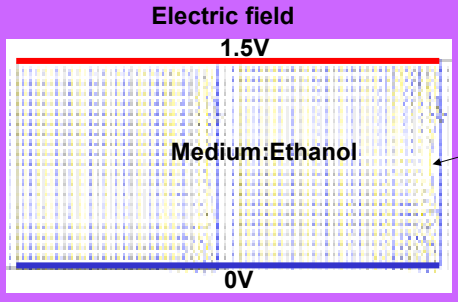


All gaps have MWCNTs!

Uniform spacing between nanotubes

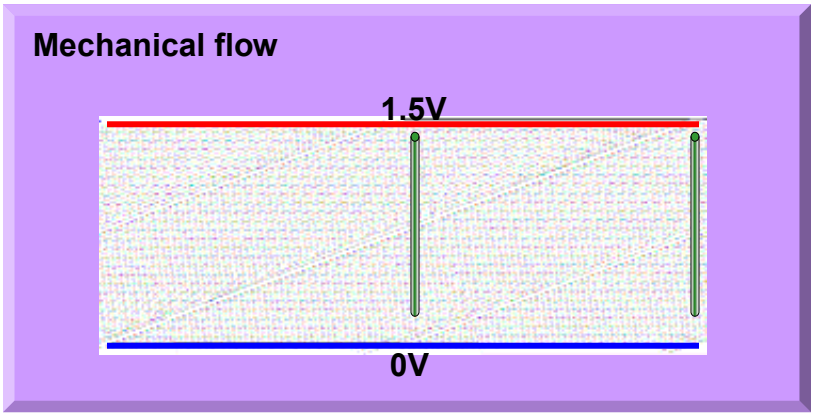
$$-\frac{dp}{\partial x}-\varepsilon E_x\frac{d^2\psi}{\partial y^2}+\mu\frac{d^2u}{dy^2}=0$$

- Navier-Stokes equation coupled with an electric field
- MacInnes model *(Chem. Eng. Sci. 2002)*



Simulation software : FEMLAB

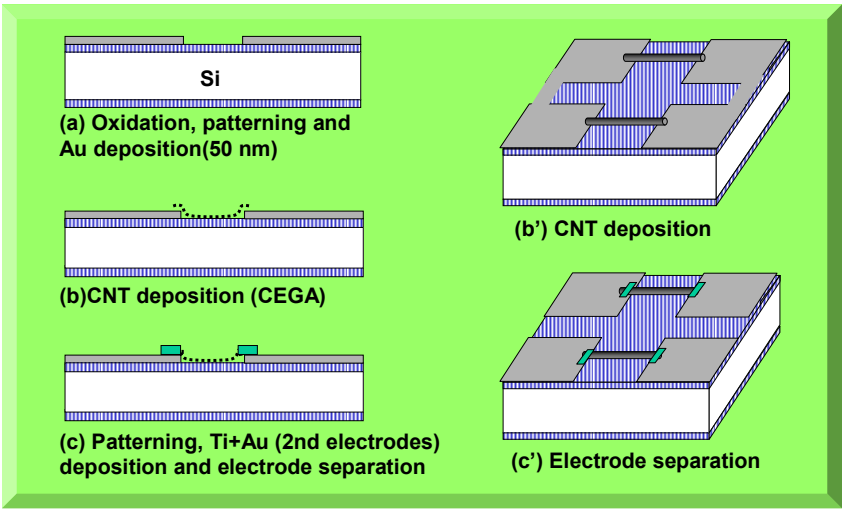
Uniform spacing between nanotubes



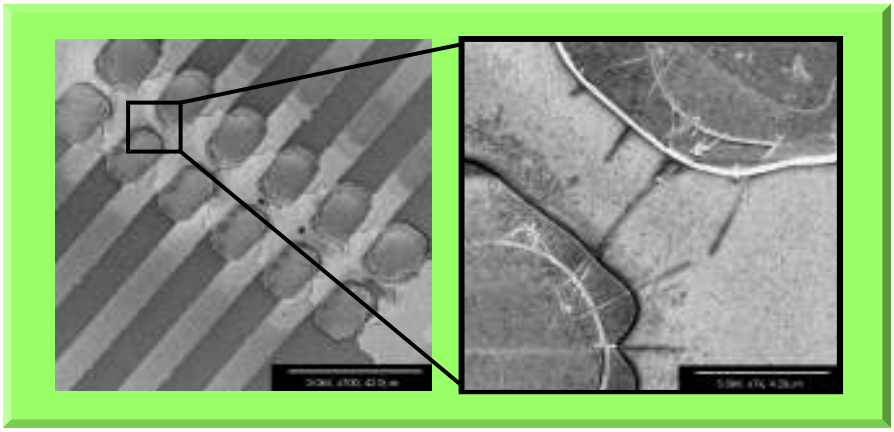
- Periodic spacing due to repulsive flow
- Similar analysis for latex bead in flow; electrohydrodynamic flow

(M. Trau, et al, Langmuir, 13, 6375, 1997)

General MWCNT device



MWCNT device *(cont'd)*

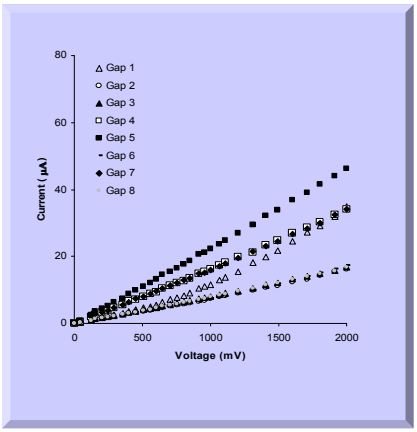


Characterization

- **Metallic from the *I-V* curve**
- **Metallic CNT's more polarizable than medium**
  (R. Krupke, Science, 2003)

$$F_{dep} \propto \left(\varepsilon_p - \varepsilon_m\right)$$

- **Contact resistances from 40k to 200k Ohm**



Fluid Flow Assisted Dielectrophoretic Assembly

Why fluid flow?

Fluid flow is characterized by Reynolds number

$$\mathrm{Re} = \frac{LV\rho}{\mu}$$

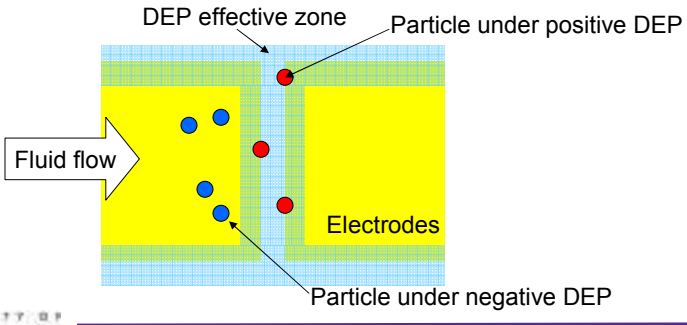
where, L: characteristic length
V: velocity of fluid
ρ: fluid density
μ: viscosity of fluid

- Since the Reynolds number ranges 0.01~10 in microfulidic channels, laminar flow forms.
- Shear force due to laminar flow in a microchannel transports and aligns nanowires**

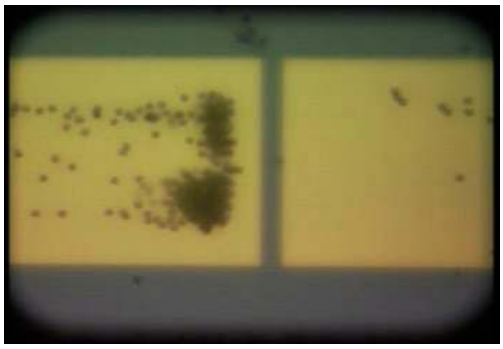
***Huang, Y. et al., Science, 2001*

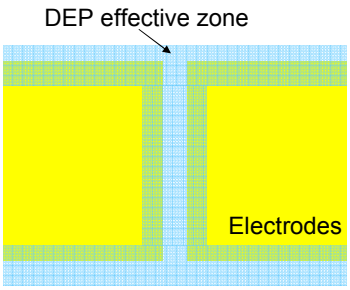
Why fluid flow? (cont'd)

- Fluid flow: can deliver nanowires to electrodes (good for long range transport): a few centimeters
- The role of the DC field in the composite field is substituted by the fluid flow; it can avoid electrophoretic force.
- Dielectrophoresis (DEP) : can attract nanowires in the vicinity of electrodes (in the range of tens of micrometers; checked by negative dielectrophoresis).



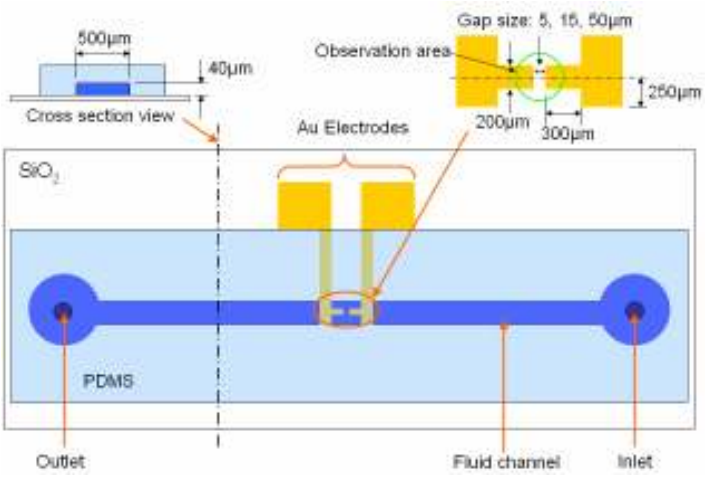
Why fluid flow? (cont'd)





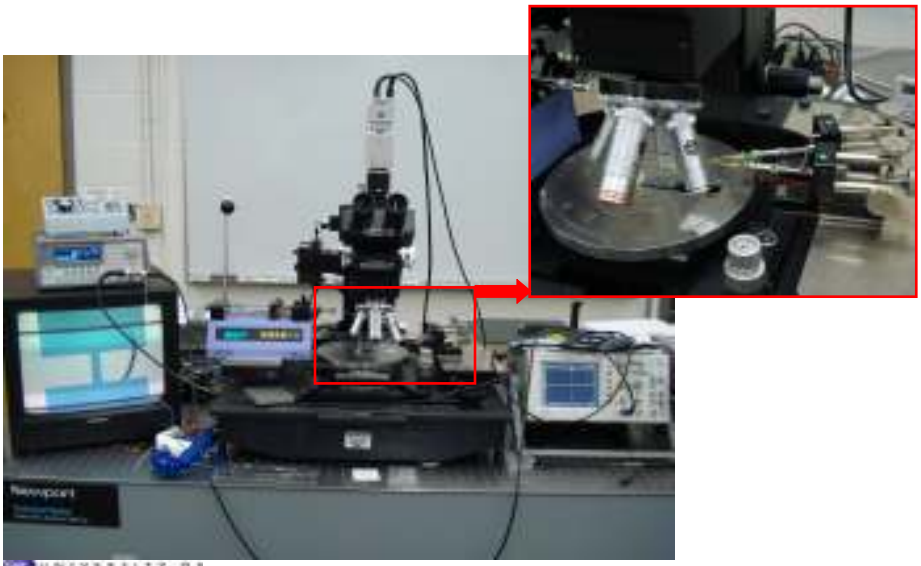
- Dielectrophoresis is working only in the DEP effective zone.
- Fluid flow assisted DEP assembly: improve the assembly process yield.
- Fluid flow: long range transport; DEP: short range assembly.

Experimental Configuration



< Layout of microfluidic device >

Experimental Set-up



Experiments

(1) Comparison between open deposition and channel deposition

- Open Deposition: Assembly process without a fluidic channel

  The nanowire solution is gently placed on electrodes in air.

- Channel Deposition: Assembly process in a fluidic channel

  The solution is injected in the inlet and transported by capillary action.

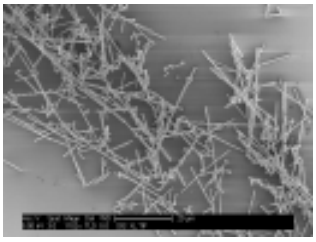
- Nanowires are suspended in ethanol.
- Applied AC voltage: 10Vpp, frequency: 5MHz

(2) Controlled Assembly of Nanowires

- To achieve uniform spacing, the fluid flow is controlled by a syringe pump with precise control of electric field.

* Dimethylformamide (DMF) is used to disperse nanowires.

Sample preparation



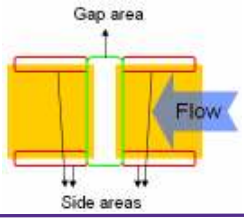
- Silicon Carbide (SiC) nanowire solution
  - Average length: 10.4μm
  - Diameter: 400nm to 600nm
  - SiC nanowires were dispersed in ethanol
  - Concentration: 2.5μg/mL
- Sonication for 5 minutes
- AC electric potential $10V_{pp}$, Frequency: 5MHz
- Drop 9μL of the solution
- Use capillary action for the channel deposition
- Assembly process is recorded through CCD camera
- All the experiments are repeated three times
- Averaged values are used to analyze the assembly phenomena.

Open Deposition vs. Channel Deposition

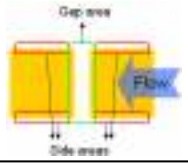
Open deposition

Channel deposition

*The AC voltage: 0.75Vpp
**The frequency: 5MHz.



Yield of nanowire deposition



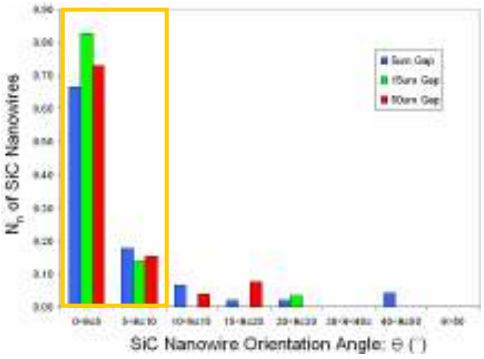
Average number of deposited nanowires for 1 minute

	Gap areas			Side areas		
Gap Size	5μm	15μm	50μm	5μm	15μm	50μm
Open deposition	6.0±5.3	0.7±0.3	3.3±3.1	13.3±1.5	3.0±3.5	12.7±6.0
Channel deposition	16.7±5.3	12.0±5.3	12.7±5.3	7.0±3.6	6.0±3.0	7.7±2.1

Regarding the channel deposition, the number of nanowires is larger in the gap area and smaller in the side areas compared to the open deposition.

- Uniform flow in the channel transports nanowires to the gap, which increases the number of nanowires in the gap area
- Random flow in the open deposition increases the number of nanowires in the side areas.

Orientation angle



The average orientation angles

5μm gap: 5.8°

15μm gap: 2.4°

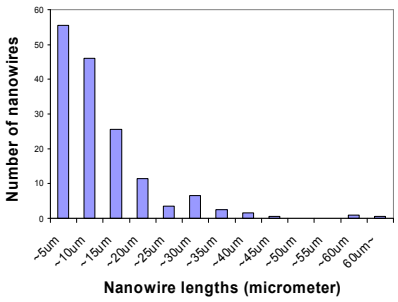
50μm gap: 3.5°

- Orientation angle distribution of the SiC nanowires after 1 minute deposition.
- Orientation angle is related to gap size and nanowire length**

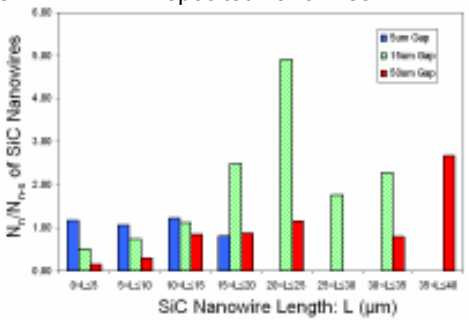
***Y. Liu, et al., J. of Physical chemistry, 2006*

Sorting upon lengths

Length distribution of original nanowires



Deposited nanowires



N_n: Normalized number of the nanowires on each gap

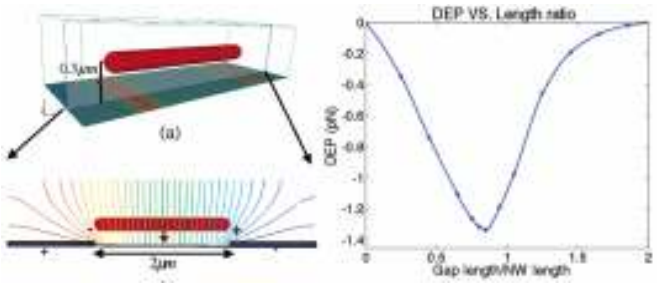
N_{n-s}: Normalized number of the nanowire source on each gap

- Nanowires are selectively attracted upon their lengths by dielectrophoresis.**

***Y. Liu, et al., J. of Physical chemistry, 2006*

Sorting upon lengths (cont'd)

- Whether the gap size becomes larger or smaller, the electric field around nanowire is weakened.
- When the length of nanowires is comparable to gap size, largest dielectrophoretic force is generated; thus nanowires can be sorted according to their lengths.



The sorting principle can be used for other particle separation.

Controlled assembly; Landing

(a) Time = 0sec. (b) Time = 2sec. (c) Time = 5sec.

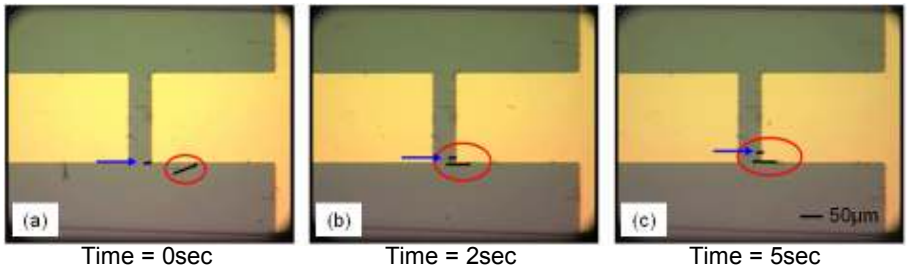
(a) A SiC nanowire in DMF approaches the gap

(b) The nanowire is anchored at the edge of an electrode.

(c) The nanowire is aligned with the direction of the fluid flow.

The AC voltage: 0.75Vpp, the AC frequency: 5MHz.
The speed of approaching nanowire in the solution: 50μm/sec.

Controlled assembly; Shifting



Time = 0sec Time = 2sec Time = 5sec

(a) A SiC nanowire is deposited on the gap.

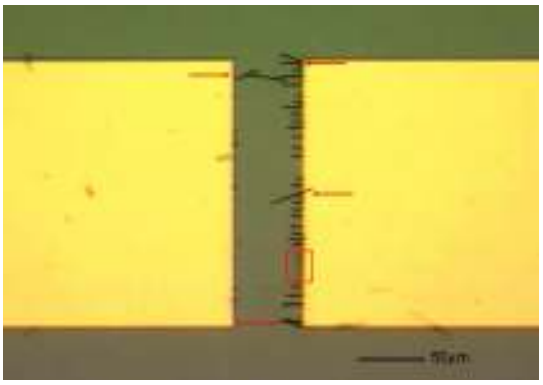
(b) Another SiC nanowire is approaching to the nanowire.

(c) The pre-deposited nanowire is shifted.

What happens if this shifting occurs whenever a nanowire is deposited?

The AC voltage: 0.75Vpp, the frequency: 5MHz.
The speed of approaching nanowire in the solution: 300μm/sec

Controlled assembly; spacing



The red arrows are not individual ones when they approached the gap, and are not considered for the spacing calculation.

Nanowires in the red rectangle cannot be calculated for the distance because the image is obscure.

Nanowires are aligned with uniform spacing in the controlled assembly and few nanowires are deposited in the side areas.

SiC nanowires in Dimethylformamide (DMF), Flow speed: 300μm/sec
Electric potential: 0.75V_{pp}, Frequency: 5MHz, Gap size: 50μm

Future direction

- Fluid flow assisted dielectrophoretic assembly can be used for massive assembly of nanowires (nanotubes).
- The fluid flow induced mechanism needs to be further investigated for smaller scale objects (e.g. single walled carbon nanotubes).
- The sorting principle should work for other bio/nano particles.
- The applications include particle separator, DNA chips, other molecular devices.

One dimensional assembly

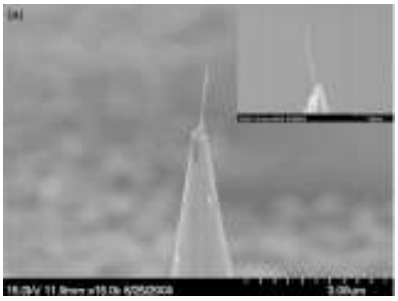
Introduction

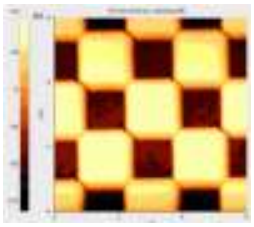
- The need for multifunctional materials is driven by recent trends in engineering industries.
- A number of investigations have been successful to achieve the multifunctionality of nanocomposites
  - A. Y. Cao et al, *Nature Materials,* 2005.
  - H. Choi et al, *Advanced Functional Materials,* 2006.
- The nanomaterials could demonstrate the superb properties due to the extremely large interface in different domains.
- As a preliminary study, hybrid fiber (Single walled carbon nanotubes + SiC nanowires) formation is demonstrated by using AC electric field and capillary action.

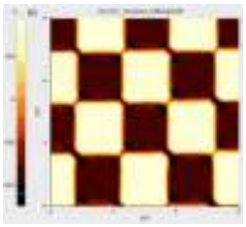
Objectives

- Fabricate hybrid fiber using an AC electric field and capillary action
  - Hybrid fibers composed of SWCNTs and SiC nanowires
- Demonstrate that both diameter and length of hybrid fibers could be controlled by manipulating parameters
  - Mixing ratio of SWCNTs and SiC nanowires, concentration of solution, immersion time, volume of solution, and withdrawal rate

Fiber formation





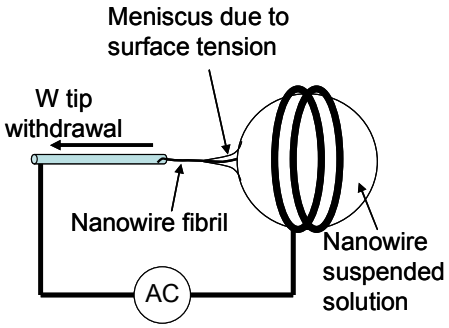


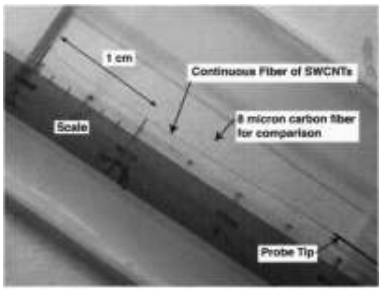
Microstructure Imaging by AFM tip and CNT attached tip.

Reliable process for CNT attached AFM tip fabrication.

Lee HW, et al., REVIEW OF SCIENTIFIC INSTRUMENTS, 2005.

Fiber formation (cont'd)





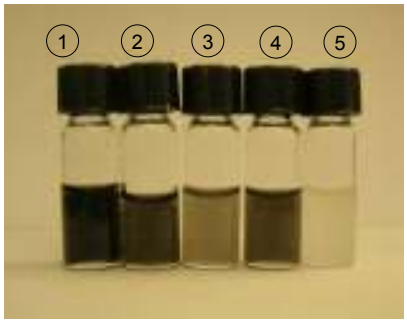
Fiber drawing process was developed by Tang et al. (1)
By using a DC field, the withdrawal rate was less than 1μm/sec, which needed to be improved; 10hours was taken for the 3cm fibril (2).

(1) Tang et al, ADVANCED MATERIALS, 2003.
(2) Annamalai R, et al. Journal of Applied Physics, 2005.

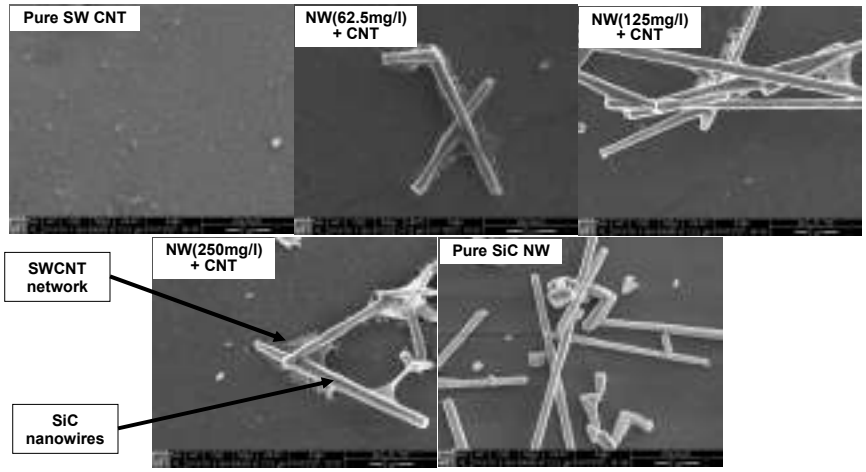
Material preparation

- Hybrid fibrils can be a solution improving both the withdrawal rate and the mechanical, electrical, thermal performance.

- Disperse SWCNTs and SiC nanowires in DMF (Dimethylformamide) respectively, and then mix the solutions.
- Prepare five mixtures.
  (1) 0mg/L (pure SWCNTs)
  (2) 62.5mg/L
  (3) 125mg/L
  (4) 250mg/L
  (5) 250mg/L (pure SiC nanowires)
  * Except (5), all bottles contain SWCNT (concentration: 120mg/L)



Material preparation

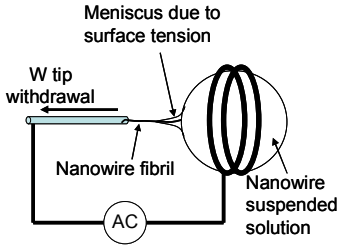


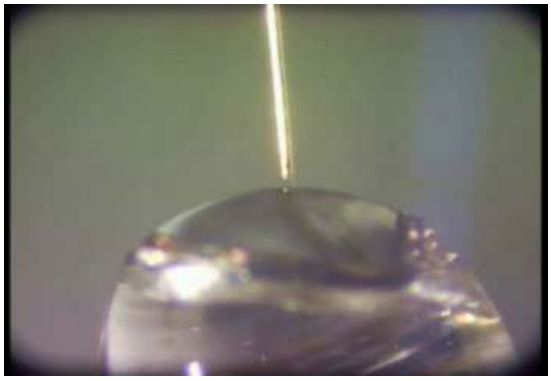
- The coverage of SWCNTs on a single SiC nanowire appeared to be uniform. It means one SiC nanowire could bring a similar amount of SWCNTs regardless of concentrations

Parameters

- Only mixing ratio was manipulated in this experiment. According to the ratio, various lengths of fibers are fabricated. Other experimental conditions were fixed.
  - Withdrawal rate: 16μm/second
  - AC electric field: 20Vpp at 5MHz
  - Immersion time: 30s
  - Immersion length: 100μm
  - Volume of each solution: 2μl

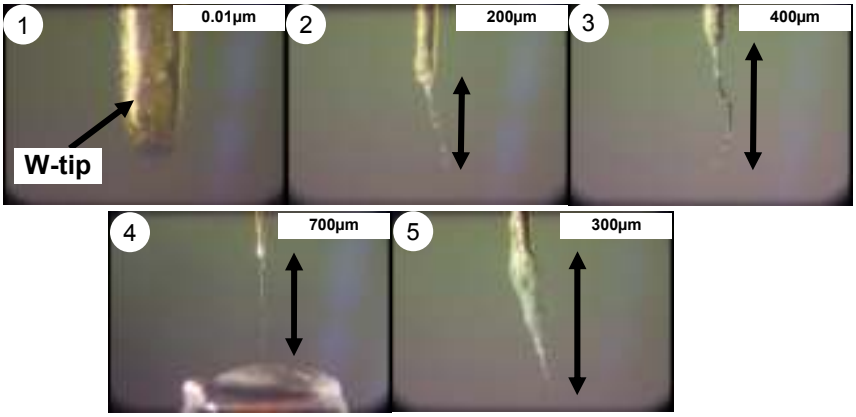
Hybrid-fibril formation





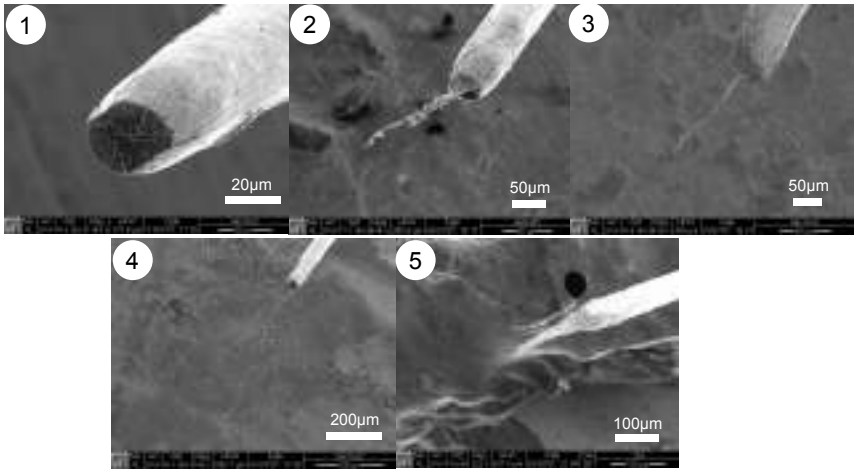
- Tungsten (W) microwire (diameter: 50μm) was prepared for the drawing.
- Fibril formation from SiC and SWCNT mixture.

Hybrid-fibril formation (cont'd)



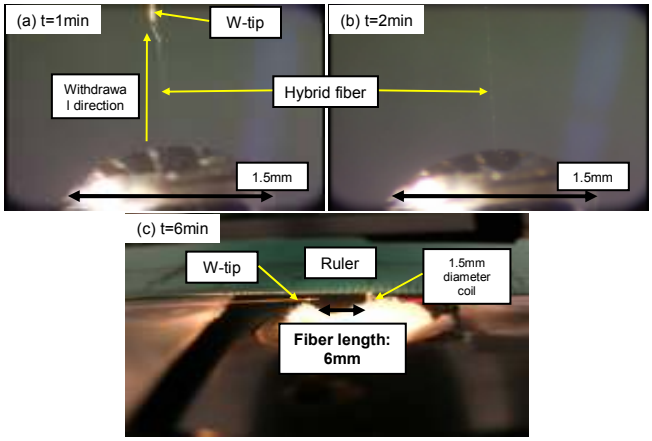
- The images show the various lengths of nanofibers according to the variation of mixing ratios of SWCNTs to SiC nanowires.
- The number in each picture is corresponding to the numbers of the prepared bottles.
- The length of each fiber is described in the inset of each figure

Hybrid-fibril formation (cont'd)



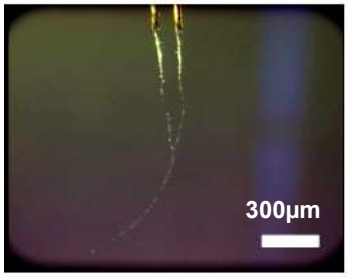
- SEM micro photos
  - The numbers correspond to numbers in previous slide

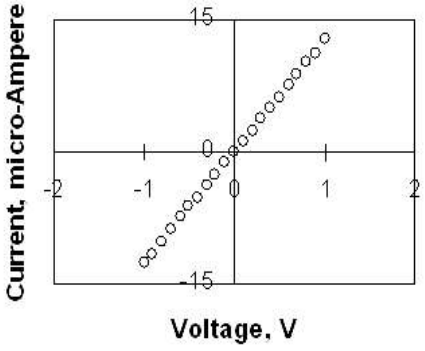
Hybrid-fibril formation (cont'd)



- A 6mm-long nanofiber forms using 2μL of solution with an AC field.
- Withdrawal rate: 16.7μm/second, which is 20 times faster than the previous work (*Annamalai R, et al. Journal of Applied Physics,* 2005.).
- Currently working on an array of fibrils.

Electrical characterization.





- The nanofibrils exhibit metallic behavior.
- The metallic response is achieved because dielectrophoresis upon AC electric field dominantly attracts metallic SWCNTs.
- The resistance of 1.8mm-long needle is ~77kΩ.

Future directions

- Longer fibrils will be fabricated by improving the supplying mechanism of nanowire solution and electric potential.
- Array of fibrils will be fabricated to make fabric, which can be used for multifunctional composite systems.
- The fabricated individual fibrils can be used for sensors and actuators.
- One of applications include a nanoneedle capturing biomolecules.

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