# Ferrofluidic Alignment of Carbon Nanotubes

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## Abstract:

The alignment of carbon nanotubes using a ferrofluid is explored. By applying a colloidal liquid suspension of ferrous nanoparticles to a wafer with CVD-grown carbon nanotubes, we observe evidence of a mechanical interaction between the nanoparticles and nanotubes facilitated by an externally-applied magnetic field. Future use of this interaction may facilitate the alignment of carbon nanotubes in micro-electronic devices.

## Introduction:

Carbon nanotubes (CNTs) have been aligned using several unique methods. For example, Ural's method [1] uses an electric field to align the CNT's during CVD growth. However, this method requires electrodes to be placed onto the wafer which take up lots of space where more CNTs could've been grown. For multi directional growths, it may be difficult to use this method, because of effects that may stem from the interaction of electric fields within the wafer area. In another method, Liu [2] has prepared chemically-patterned wafers that favor, or oppose, the union of CNTs in liquid suspension. However, one cannot control the length of which CNT's adhere to the chemically patterned surface.

With this method, we attempt to use ferrofluid (i.e. a colloidal suspension of surfactant-coated, nanometer-sized, ferrous particles, suspended in a carrier liquid) to forcibly align CVD-grown CNTs using a mechanical "raking" of the magnetic nano-particles across the CNTs, as shown in Figure 1.

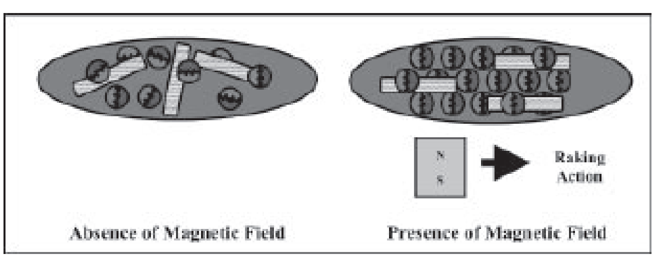


*Figure 1: Alignment of carbon nanotubes using a ferrofluid.*

## Experimental Procedure:

Silicon (100) p-type wafers (100 mm diameter, 525 $\mu$m thickness, (0.2 Ω-cm resistivity) were MOS-cleaned ($NH_3O_4$ & HCl) and spin-rinsed in a Verteq superclean 1600 dryer. Afterwards, ~210 nm of wet-HCl oxide was grown in 28 minutes at 1000°C.

The application of HMDS followed by Shipley S1805 resist at 4000 rpm for 60 sec, resulted in a resist coating of ~700 nm. A soft-bake at 90°C for 60 seconds followed. Immediately after, a 0.29-sec exposure in the GCA AutoStep 200 stepper was done. A post exposure bake at 115°C for 60-sec followed by a 150-sec development in the MIF300 using the Hamatech-Steag opened holes for our catalyst islands. De-scum was completed using an oxygen-clean recipe (50 SCCM $O_2$, 30 mTorr, 150W, 10°C) in the Oxford-80 RIE system.

Using a CVC-4500 e-beam evaporator ~5Å of iron was deposited across the wafers, followed by scribing/breaking into individual chips, and acetone lift-off (10-min) with a final isopropanol rinse.

Our substrates were then inserted into a 1-inch diameter quartz tube furnace (Lindberg/Blue Model #HTF55122A) and ramped to 700°C while flowing 0.80L/min of argon. Purging of the tube occurred for 10-min with 0.80L/min of argon and 0.15L/min of hydrogen at 700°C. Adding 5.5 $cm^3$/min of ethylene ($C_2H_4$) for 6-min resulted in carbon nanotube growth. Cool-down at 12°/min with 0.80 L/min flow of argon completed the process. Finally, a droplet of EMG 707 ferrofluid (FerroTec) was applied with a pipette onto the top surface of each chip and a neodymium-iron-boron permanent magnet (~2000G) was slid underneath. The ferrofluid applied to each chip reacted to the magnetic field by flowing controllably across the surface, thereby producing a mechanical "raking" of the CNTs. Following 5-10 swipes of the magnet, the chips were rinsed in a beaker of de-ionized water to remove any remaining ferrofluid.

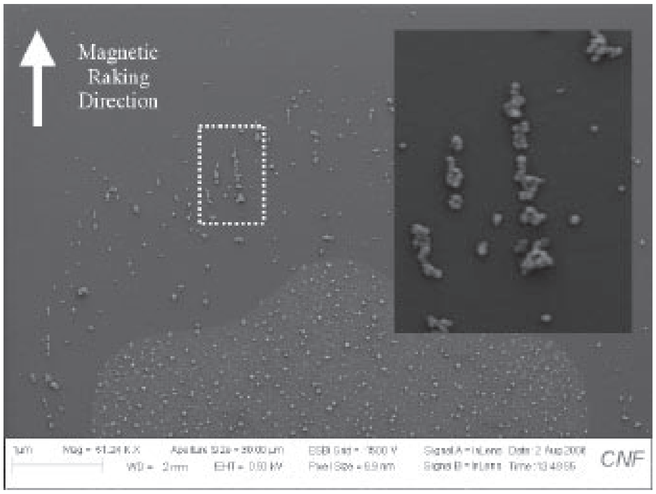


*Figure 2: Catalyst island with carbon nanotube debris field.*

## Results and Conclusions:

SEM analysis of the CNTs using a Zeiss Ultra55 before/after ferrofluid-raking showed varied results.

On some catalyst islands, the raking action was disastrous to the CNTs, leaving behind a debris field, with an outline shape similar to the shape of the catalyst island (i.e., round, square, etc). These debris fields (i.e., bits and pieces of broken-up nanotubes) were always shifted, relative to the islands, in the raking direction, with some evidence of alignment, as shown in Figure 2.

On other catalyst islands, we observed markedly different results. For example, Figure 3 displays SEM images of the same catalyst island before and after ferrofluid-raking. In the "Before" image, we see a nanotube forest wherein some of the nanotubes are in-focus and some are not. Many of the nanotubes had grown upward from the surface of the wafer. We believe that this growth was a consequence of the quartz boat that we used to hold the wafer chips in the furnace. Interestingly, at times, we could see certain portions of the carbon nanotubes moving about, depending on the settings of the SEM. In the "After" image, we notice that most of the carbon nanotubes that had grown out of the plane of the wafer were "scrubbed" away, leaving behind only those that were strongly pinned to the surface by Van Der Waals forces. In a few individual cases, we also noticed that a single tube had changed shape because an open loop in a tube that had been sticking-up into the air was folded down onto the surface as a result of the raking action.

In conclusion, we have successfully shown a mechanical interaction between the ferrous nanoparticles within a ferrofluid and CVD-grown CNTs.

## Future Work:

By reducing the strength of the magnetic field and/or diluting the ferrofluid, it should be possible to accomplish CNT alignment without any destructive effects. It would also be interesting to try ferrofluids with different carrier liquids. Finally, we would like to try alignment of CNTs in liquid suspension. In other words, one would introduce CNTs directly into the ferrofluid and then see if a magnetic field could be used to control the alignment of the CNTs.

## Acknowledgements:

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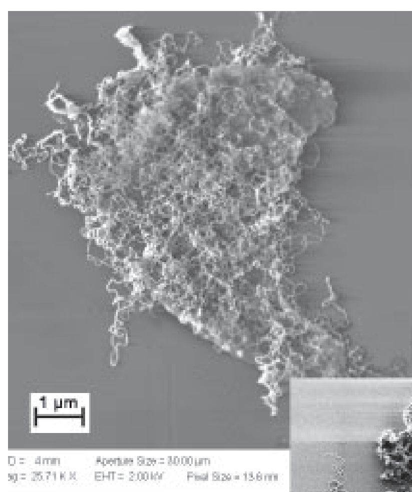
## References:

[1] Ural, Li and Dai, "Electric-Field-Aligned Growth of Single-Walled Carbon Nanotubes on Surface", Applied Physics Letters, Vol.81, No.18, Oct.2002, pp.3464-3466.

[2] Liu, Casavant, Cox, Walters, Boul, Lu, Rimberg, Smith, Colbert and Smalley, "Controlled Deposition of Individual Single-Walled Carbon Nanotubes on Chemically Functionalized Templates", Chemical Physics Letters, Vol.303, Apr. 1999, pp. 125-129.



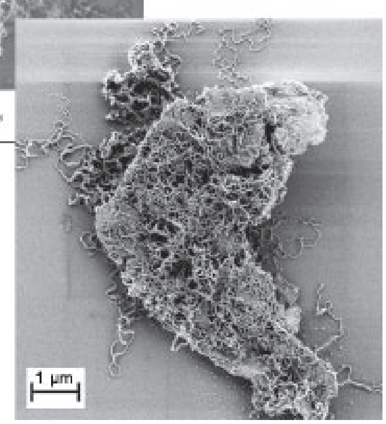




*Figure 3: Before (left) and After (right) images.*