Multiple Transfers of Single-Walled Carbon Nanotubes on Silicon Wafers

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Abstract:

Single-walled carbon nanotubes (SWCNTs) have many applications, including high speed transistor devices (see Figure 1). SWCNTs are grown on single-crystal quartz wafers and then transferred onto silicon wafers by a process that involves gold evaporation and thermal release tape. When they are grown, there are usually between 4 to 10 SWCNTs per micrometer on the surface of the quartz wafer. Increasing the number of SWCNTs per micrometer increases the electrical performance of transistor devices linearly [1]. In this project, we attempt to perform multiple transfers of SWCNTs onto the same wafer in order to increase their density. One of the problems we face is that residue from the initial transfer is preventing any additional transfers from succeeding. We approach this quandary using two different techniques: applying different adhesives and using various chemical solutions to clean any tape residue that may affect the transfer process. We use scanning electron microscopy (SEM) to detect any improvement in surface cleanliness and observe the damage, if any, done to the SWCNTs by our process using probing equipment to measure I-V characteristics and performance. From our results we were able to show that multiple transfers did indeed improve performance even though the multiple transfers were not 100% successful.

Introduction:

Carbon nanotubes are nanostructures that are members of the fullerene family. Their diameters vary from 0.5 nm to 5 nm and the SWCNTs we worked with were between 1 to 2 nm. SWCNTs can be either metallic or semi-conducting depending on its chirality. We grew the SWCNTs using chemical vapor deposition (CVD) where we placed iron catalyst in lithographically defined stripes approximately 50 μm apart on a single-crystal quartz wafer [2]. The SWCNTs grew from catalyst stripe to catalyst stripe and were well aligned. The density of the SWCNTs as grown was between 4 to 10 SWCNTs/μm. Our target density was between 200 and 250 SWCNTs/μm.

Experimental Procedure:

Although we were able to grown well-aligned SWCNTs on quartz wafers, we needed to transfer them onto silicon wafers while maintaining their density and alignment. After we grew SWCNTs, we deposited 100 nm of gold, using electron beam evaporation, onto the quartz wafer. We applied a thermal release tape and peeled off the tape along with the gold and SWCNTs. Once we successfully removed the SWCNTs from the quartz wafer we applied the thermal release tape on a silicon wafer and heated up the wafer at 120ºC at which point the thermal release tape fell off, leaving the layer of gold on top of the SWCNTs. We removed the gold layer using a dry etch with oxygen plasma followed by a wet etch with gold etchant [2].

Since our target density was from 200 to 250 SWCNTs, we needed to perform multiple transfers to increase the density.

TABLE 1

Cleaning Techniques		
Chemical Name	Formula	Result
Ethyl Ether	CH_3-CH_2-O-CH_2-CH_3	Failed
Ethyl Acetate	$CH_3COOCH_2CH_3$	Failed
Petroleum Ether	C_7H_{16} + C_6H_{14} + C_5H_{12}	Failed
Hexane	C_6H_{14}	Failed
Cyclohexane	C_6H_{12}	Failed
Toluene	C_7H_8 ($C_6H_5CH_3$)	Failed
Acetonitrile	CH_3CN	Failed
Piranha	H_2O_2 + H_2SO_4	Destroyed CNTs
Aqua Regia	HNO_3 + HCl	Inconclusive
Hydrazine	N_2H_4	Failed
Ozone	O_3	Failed

TABLE 2

Adhesion Promoters		
Name	Original Purpose	Result
Omnicoat	Improves adhesion to gold	Failed
BCB	Advanced Electronic Resin	Failed
Polymide	High-Temperature Adhesive	Failed
AP410	Photoresist Adhesion Promotor	Failed

Table 1, top: Table of cleaning techniques we used in our attempt to clean off the tape residue.

Table 2, bottom: Table of adhesion promoters we used in our attempt to promote the adhesion of gold.

When we attempted to perform multiple transfers using our standard procedure, the gold and SWCNTs did not adhere to the surface of the wafer because the layer of gold would come off along with the tape when it was heated. We found out that there was a layer of residue, whose properties were unknown, on top of the original transfer and that was preventing any additional transfers taking place.

We attempted to remove the residue using all of the chemicals listed in Table 1 by soaking the wafer with residue in those chemicals for different periods of time ranging from 30 seconds to several hours. None of the chemicals were successful in cleaning the residue with the exception of Piranha, but Piranha also destroyed the SWCNTs. We tried using Aqua Regia as a substitute for our gold etchant, but our results were inconclusive. In addition to cleaning, we tried using different adhesion promoters as listed in Table 2 to promote gold adhesion. All of the adhesion promoters failed to create successful multiple transfers and, sometimes they performed worse because they did not allow the gold etchant to remove the layer of gold thoroughly.

From our results, we concluded that we needed to try a different procedure of transfer. We developed a process in which we used standard photolithography to cover with photoresist the specific areas of the wafer where the transistor channels would be. That area was now protected from dry etching where as the area with SWCNTs not covered in photoresist was not protected. We then used oxygen plasma as a dry etch to etch away all of the residue and SWCNTs where we didn't need SWCNTs and then performed a second transfer.

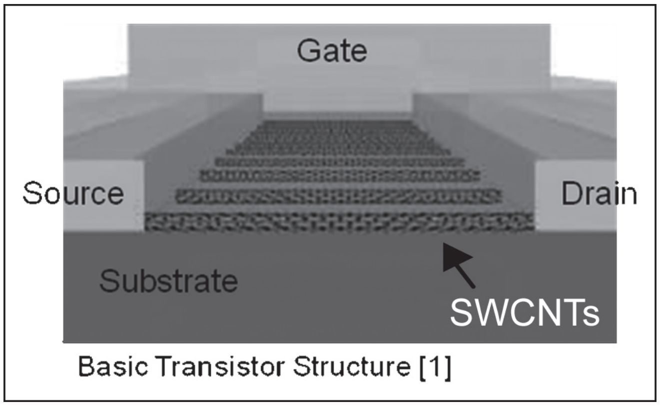

Figure 1: The SWCNTs serve as the channel between the source and the drain.

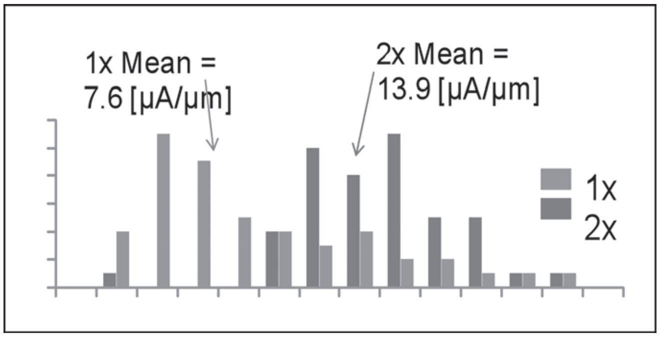

Figure 2: We can clearly see that the 2x distribution is shifted towards the right while the 1x distribution is shifted towards the left.

Results and Conclusion:

Our results from this new procedure were successful. The removal of residue and SWCNTs in places where we did not intend on having transistor channels increased the overall clean area of the wafer and thus improved the overall adhesion of the second transfer even in those areas where we left the residue and SWCNTs. We tested the performance of our second transfer by measuring the current density of transistors that experienced a second transfer and of those who only experienced one transfer (see Figure 2). From our results, we were able to show that transistors with two transfers performed almost twice as well as those with only one transfer. This proves that we increased the density of our SWCNTs by a factor of two.

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