ACTIVATION OF CNT NANO-TO-MICRO CONTACT VIA ELECTRICAL BREAKDOWN
Berkeley Sensor and Actuator Center, University of California at Berkeley
Telephone: 1-510-642-8983 Fax: 1-510-643-6637, Email: yqjiang@berkeley.edu

ABSTRACT
The "healing" of nano-to-micro electrical contact between a single carbon nanotube (CNT) and silicon micro structure has been demonstrated using the technique of electrical breakdown. Experimental results show that the resistance of an in-situ synthesized CNT was "healed" from an original value of infinite to 7MΩ. The experimental breakdown voltage is 10V and the electrical field is estimated as 5×10^7V/cm for a 2nm-thick native oxide layer, which is consistent with the analytical breakdown value. This process helps improving the resistance of nano-to-micro contacts and increase device yield by activating seemingly non-functional CNTs in nano electromechanical systems (NEMS).

1. INTRODUCTION
The unique characteristics of carbon nanotubes (CNTs) such as high surface area-to-volume ratio and excellent electrical and mechanical properties have attracted extensive studies in various device applications, including nano sensors [1,2]. One of the key technical challenges in constructing CNT-based sensors is the nano-to-micro contacts. Understanding and coping with the electrical characteristics of these contacts are vital to improve the whole system performance. For example, researchers have demonstrated that CNT devices could have excellent contact behaviors using large metallic electrodes by means of E-beam or Focused Ion Beam deposition processes [3,4]. Theoretical and experimental results have shown that devices could have Schottky barriers [5,6]. In state-of-art practice, CNTs are fabricated first, selectively transferred to proper spots on a substrate, and nano-to-micro contacts are constructed.

A different, while more natural nano-to-micro contact can be realized using the in-situ CNT synthesis and assembly process as implemented previously between two MEMS bridges[7-9]. The resulting nano-to-micro contacts have much smaller contact areas in compared with other integration technologies. In this paper, we present and address issues on these nano contacts; propose and demonstrate the technique of using electrical breakdown to effectively activate the nano-to-micro contacts. Several orders of magnitudes in resistance reduction for poorly-connected CNTs have been demonstrated. Based on the experimental results, possible mechanisms behind this method are discussed.

Y. Jiang and M. Q. H. Zhang contributed equally to the work presented in this paper.

2. NANO-TO-MICRO CONTACTS
Our local synthesis and assembly process starts with joule heating of a silicon microstructure in acetylene environment with the electrically-guided assembly technique to direct the CNT growth toward a secondary silicon structure [8]. Two types of nano-to-micro contacts could be formed when CNTs arrived at the secondary silicon electrode as illustrated in Figure 1. In the tip-growth mechanism, the hot Ni/Fe catalyst particle at the CNT tip lands on the cold secondary structure and stops the growth process immediately because the catalyst is cold after the contact. The root-growth mechanism, on the other hand, will have catalyst particles on the hot growth electrode such that the growth process can continue and often result in line contact on the secondary electrode. Figure 2 shows two SEM pictures corresponding to these two contact cases, respectively.

These multi-walled CNTs are typically metallic with diameter in the range of 20±15nm. Experimentally, it has been observed that some as-synthesized and assembled single CNTs have shown excellent ohmic contact behaviors [8,9] while some have poor responses. Figures 3(a) and (b) are two examples of the good and poor IV nano-to-micro contacts from two different samples. The good contact gives an overall resistance of 2.5MΩ while the poor contact has infinite resistance. The poor I-V responses make the device useless and prompt investigations into the fundamental causes of these two very different behaviors as well as possible remedies. It is well-known that native oxide can easily grow on top of the silicon surface as illustrated in Figure 1, and therefore, the role of native oxide is studied first and the procedure of electrical breakdown is developed and investigated experimentally.

Figure 1. Illustrations of the two types of CNT nano-to-micro contacts as the result of the two growth mechanisms: (a) Tip-growth and (b) Root growth, due to the position of the catalyst particle on the tip and root of the CNT, respectively.
3. BREAKDOWN PROCESS

The breakdown process is carried out in the argon gas environment with a partial vacuum pressure of about 8 inch-Hg (2.7×10^4 Pa). Experiments in regular air environment show a high possibility of damaging or breaking the CNTs before the occurrence of the breakdown probably due to the existence of oxygen in air. HP 4145B Semiconductor Parameter Analyzer is used to simultaneously supply the necessary voltages for the breakdown procedure and monitor the I-V responses. The procedure starts with a low voltage scan, typically from -0.5 to +0.5V. The scanning range is then gradually widened until an abrupt current jump is observed.

Figure 4 shows a typical electrical breakdown experiment. When the applied voltage is lower than 7V, the current is in the low nano-Ampere range. After applying a voltage of 10V, the current level is about 1000nA, or four orders of magnitude increment. Detailed characterizations are recorded in a different sample. Figures 5(a)-(d) show the progression of the CNT sample during the breakdown process. When the maximum applied voltage increased from 1V to 6V (Figures 5(a) and (b)), no meaningful changes can be identified as the noises seem to dominate the outputs and the magnitude of current is always lower than 1nA. After 8V is applied (Figure 5(c)), a notable response is observed with the current output being one order of magnitude higher than the nA-level. It is noted that during the synthesis and assembly process, the voltage potential between the growth and secondary electrode is also about 8V and this could be the reason that we were able to detect the CNT connection as it was formed [9]. However, a close examination shows that the current in low voltage range are still essentially the same as in Figures 5(a) and (b). When the voltage scan is increased to 10V (Figure 5(d)), the current drastically jumps from nA to 10^4nA level, indicating electrical breakdown.

Figures 6(a) and (b) compare I-V responses of the same CNT sample shown in Figure 5 before and after the breakdown treatment, respectively. The initial CNT resistance is not definable and was reduced to 7 MΩ with a good ohmic profile after the breakdown treatment.
4. DISCUSSIONS

The breakdown testing of the CNT sample shown in Figure 5 was performed immediately following the synthesis and assembly process without venting the chamber such that the influence of external environment may be excluded. Although our feedback system clearly indicates successful CNT contact during the synthesis and assembly process, the device is not functioning normally until after the electrical breakdown procedure. Defects along the CNT can contribute to the high resistance, but they are not likely to be “healed” by using a high bias voltage. It appears that the nano-to-micro contacts between CNT and the secondary silicon electrode are the main cause of the observed phenomena.

Since the silicon micro structures have been fabricated long before the CNT synthesis process, there should be a layer of naturally grown native silicon oxide on the secondary silicon electrodes. If a thin layer of native oxide exists, it will allow only a small amount of leakage current to flow under a low voltage supply. However, when the applied voltage is gradually increased, larger electrical field can be generated across the nano-to-micro contact. Electrical breakdown can happen when large amount of electrons are attracted by the electrical field to cause high electrical current. High electrical current, in turn, can generate localized heating across the contact and could cause local melting of the thin native oxide to open up a conductive path. Afterwards, the device has been “healed” due to the breakdown process which is irreversible. The typical thickness of the native oxide layer is about 2nm [10].
and the breakdown voltage in our experiments are about 10V. The estimated breakdown electrical field is calculated as $5 \times 10^7$ V/cm, consistent with typical electrical breakdown field of silicon oxide [11]. This further explains the breakdown behavior of these CNT devices.

Further examinations are conducted by studying the synthesis and assembly setup as illustrated in Figure 7. The growth electrode typically requires about 7V in order to provide enough joule heating to achieve the CNT growth temperature. On the other hand, the electrically-guided assembly process is typically conducted with a bias voltage of 5V between the lower-end of the growth electrode and the secondary electrode (V=ground). As the result, the potential along the silicon growth electrode varies from $+12V$ to $+5V$. Meanwhile, the secondary electrode is always connected to the ground throughout the synthesis. If the CNT growth position on the growth electrode is close to the high-potential end, the potential difference between the CNT and secondary electrode is 12V. Under such high voltage, the native oxide can be automatically broken down as soon as the contact is formed. However, if the growth position of CNT is near the low-potential region, the native oxide could withstand that potential difference and lead to a poor contact. The breakdown procedure as described in this paper can breakthrough the nano-to-micro contact afterwards. Another observed phenomenon is that if the contact is formed on the top surface of the secondary silicon, a good ohmic contact is the typically result. This could be explained as the thin catalyst layer there prevents the formation of native silicon oxide. Note that the sidewall of the secondary electrode does not have such a catalyst layer due to the angled evaporation of the catalyst. These provide plausible reasons that some of the as-synthesized CNT devices possess good contacts while others don’t.

5. CONCLUSIONS

Poor nano-to-micro contacts can significantly hinder the development of devices based on one-dimensional nano structures. The electrical breakdown method presented and demonstrated here provides an effective way to address problems originated from native oxide layers. Experimental results show that, by breaking through the native silicon oxide layer at the CNT-to-silicon contacts, the resistance of the overall CNT device can decrease significantly from infinite to 7MΩ with good ohmic profile. The breakdown procedures have been used to heal several CNT devices and the estimated electrical breakdown electrical field of $5 \times 10^7$V/cm matches with the typical electrical breakdown field of silicon oxide. Furthermore, explanations of both good and poor CNT contacts from as-synthesized device have been proposed, including: (1) potential differences between theCNT and the secondary electrode during the synthesis and assembly process, and (2) the prevention of oxidation due to the protection of the catalyst layer. As such, this study might also help systems based on other one-dimensional nano structures that have similar issues of native oxide on the nano-to-micro contacts.

ACKNOWLEDGEMENTS

The authors would like to thank Brian D. Sosnowchik for creating the IV data-collection software using, Heather Chiamori for the help fabricating the MEMS structure, and Qin Zhou for valuable discussion and suggestion. This project is supported in part by a DARPA MEMS/NEMS S&T program.

REFERENCES