Nanoscale Welding by AFM Tip Induced Electric Field

Haibo Yu1,2, Niandong Jiao1, Zaili Dong1, Yanli Qu1, Wen J. Li1,3,* and Yuechao Wang1

1Robotics Laboratory, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang, China
2Graduate University of the Chinese Academy of Sciences, Beijing, China
3Centre for Micro and Nano Systems, The Chinese University of Hong Kong, Hong Kong SAR, China

Abstract — The most difficult challenges in fabricating SWCNT-based nanosystems or nanodevices have proven to be the assembly and anchoring of SWCNTs to form a stable physical and electric contact between SWCNTs and the electrodes. For example, for SWCNT-based nanosensors or field effect transistors (FETs), the need to fix the SWCNT between electrodes is extremely important, i.e., it affects the electronic transport properties at the connection point. Currently, researchers usually focus on the assembly between SWCNTs and the electrodes by using dielectrophoresis (DEP), direct growth, or atomic force microscopy (AFM). In this paper, we present a new method to realize nanoscale welding by using an AFM tip coated with conductive materials. This method is very useful in welding the SWCNTs on the micro electrodes after the manipulation of the SWCNTs in between the microelectrodes by AFM-based or DEP-based manipulation. In our experiments, we first assembled individual SWCNTs or bundles of SWCNTs between two electrodes using DEP force. Then, SWCNTs are welded on the surface of the electrodes when a bias impulse voltage is exerted between the AFM tip and sample, which produces an electric field. The experimental results have demonstrated that SWCNTs can effectively be welded on the surface of the electrodes.

Keywords — AFM, DEP, Nanodevices, Nano-welding, SWCNTs

I. INTRODUCTION

Single-walled carbon nanotubes (SWCNTs) have attracted strong attention since they were discovered in 1991, due to their unique nanoscale mechanical structures and remarkable electronic properties [1, 2]. SWCNTs can be metallic or semiconducting, depending on their diameters and chiralities [3]. Up to now, single semiconducting SWCNT has been demonstrated theoretically and experimentally feasible in fabricating field effect transistors (FETs), memories, and logical devices [4-6]. On the other hand, single metallic SWCNT can be used to fabricate single electron tunneling devices [4]. Moreover, both metallic and semiconducting SWCNTs are the most promising materials in building basic blocks for the application of nanosensors, due to their extraordinary mechanical strength, chemical stability, and transport properties being extremely sensible to the local environment. The changes of the SWCNT electric and transport properties can be detected when SWCNTs are connected between the two micro electrodes to form a basic electric contact or a FET structure. These properties will miniaturize the size of the sensors and enable them to have high sensitivity, fast response, and low power consumption.

Many challenges need to be resolved before large scale usage of SWCNTs in commercial applications can be realized. However, the biggest challenges are to assemble SWCNTs between the two electrodes, and to realize the reliable contact between SWCNTs and the micro electrodes. In the past few years, many techniques have been developed to fabricate SWCNT-based devices on the nanoscale [7-10]. Recently, AFM has been used in the field of immobilizing or soldering of SWCNTs to the surface of silicon or metal electrodes [11, 12].

In this paper, we will first discuss the electric field around a conductive AFM tip by providing a model to describe the local electric field and macroscopic electric field. We will then report the application of DEP to assemble SWCNTs between electrodes and the application of AFM to weld SWCNTs on the surface of the micro electrodes. In our experiments, position sensitive detector (PSD) signals are used as feedback to control the manipulation of nanowelding.

II. NANOSCALE WELDING SYSTEM BASED ON AFM NANOMANIPULATION SYSTEM

A. Nanoscale welding system based on AFM

In the past few years, the atomic force microscopy (AFM) has been demonstrated to be one of the most useful tools in the field of nanoscale observation and manipulation. In addition, the AFM has also been shown to be capable at performing nanowelding using a conductive AFM tip. Figure 1 illustrates the schematic nanowelding system based on an AFM tip. The sample is electrically connected to a standard steel sample puck using conductive adhesive. The AFM tip is coated with a layer of metal. In order to produce an induced electric field, a negative bias voltage is exerted from the conductive AFM tip to the sample platform.

![Figure 1. Schematic representation of the nano-welding system based an atomic force microscopy (AFM).](image_url)
In the process of nanowelding, the conductive AFM tip acts as the field evaporation source. In order to sputter metal atoms from the conductive AFM tip, it is necessary to produce an extremely high electric field around the region of the AFM tip. The edge atoms on the conductive AFM tip can be ionized and be sputtered at the presence of extremely high electric field. Such high electric field can be obtained when using the local field enhancement technique with a very sharp conductive AFM tip. When a sharp conductive AFM tip is used, the electric field lines will be concentrated around the region of the AFM tip edge. Therefore, the macroscopic electric field required to induce metal deposition is reduced to a few V/nm. Additionally, electric field can also be enhanced through reducing the distance between the tip and the sample surface. Therefore, the key points to realize nanoscale welding using field evaporation are to use the sharp AFM tip and to reduce the distance between the tip and the sample.

B. Electric field around the conductive AFM tip

In order to simulate the electric field around the tip, the conductive AFM tip is simplified with a conductive solid sphere, as shown in Figure 2. The sample platform can be regarded as a conductive plane. For sphere-plane geometry, the electric field can be estimated using finite element method (FEM). The radius of the solid sphere equals the radius of the AFM tip.

In the simulation, the distance between the bottom of the conductive AFM tip and the surface of the substrate is 20 nm. The radius of the sphere is 10nm. A negative bias voltage with -10V is introduced to the conductive solid sphere. So, the surface potential on the solid sphere is -10V. The plane is connected with the ground. The potential difference between the conductive solid sphere and the conductive plane induces a space electric field around the solid sphere.

Figure 3 shows a plot of the electric field, which describes the electric field distribution on the slice through the center of the solid sphere.

![Figure 3. The electric field around the solid sphere. The maximum electric field is about 1.37 x 10^9 V/m.](image)

As expected, the electric field is highest at the bottom of the conductive AFM tip. The inner electric field of the solid sphere is zero. The maximum electric field is about 1.37 x10^9 V/m. However, it usually needs extremely high voltage to produce such high electric field using the conventional field evaporation.

Figure 4 shows the electric field variation from the bottom of the solid sphere to the surface of the substrate.

![Figure 4. The relationship between the electric field and the distance.](image)

From Figure 4, the local electric field and the macroscopic electric field can be written as

$$E_{\text{local}} = \beta \cdot \frac{V}{d}$$  \hspace{1cm} (1)

$$E_{\text{macros}} = \frac{V}{d}$$  \hspace{1cm} (2)
where \( V \) is the applied voltage, \( d \) is the distance between the AFM tip and the sample platform, \( \beta \sim 1/r \) is the field enhancement factor.

### III. Fabrication Process of Micro Electrodes and Nanoassembly of SWCNTs

#### A. Fabrication process of micro electrodes

Figure 5 shows the fabrication process of micro electrodes (Fabricated by the Thirteenth Research Institute, CETC). The process starts with a doped silicon substrate (~500µm, 0.05-0.20 D/cm), as shown in Figure 5(a). The silicon is first oxidated, to produce a 100 nm thick silicon oxide on the top surface of the substrate. Silicon oxide acts as the dielectric layer, as shown in Figure 5(b). Then, a layer of chromium (~20 nm)/gold (~30 nm) is deposited by the sputtering method, as shown in Figure 5(c). After that, a layer of photoresist is spun and patterned. The exposed areas are developed and the chromium/gold is etched, as shown in Figure 5(d) and (e). After the lithography process, micro electrodes with 1µm gap are fabricated, as shown in Figure 5(f).

#### B. Nanoassembly of SWCNTs

In our experiments, the raw sample of SWCNTs is synthesized by the hydrogen arc-discharge method (Provided by Shenyang National Lab for Materials Science). These as-prepared SWCNTs are first dispersed. The typical dispersion procedure is that 2.5 mg of raw SWCNTs and 1% weight of the surfactant sodium dodecyl sulfate (SDS) are added into 5ml DI-water, and the dilution is then sonicated for 3 hr at room temperature. The sample of as-dispersed SWCNTs is then centrifugated to purify for half an hour at a relative centrifugal force of 45,000g (25,000rpm) using the ultracentrifuge at 4°C.

In our experiments, SWCNTs are used to fabricate carbon nanotube field transistor (CNT-FET). The two electrodes are defined as source and drain, and the doped silicon acts as the back gate. The height of the electrodes is about 50 nm. SWCNTs are first aligned between two micro electrodes with a 1µm gap using DEP force, i.e., applying a 10 V peak to peak AC voltage at 10 KHz.

As shown in Figure 6, SWCNTs cross the gap to form an electric contact between the two electrodes.

#### IV. Nanowelding Experiments

##### A. Nanowelding on the surface of micro electrodes

Atomic force microscopy (AFM) used in the experiments is the DI Dimension 3100 (Veeco Instruments Inc.) with NanoMan®. The AFM probe used in the welding process is a conductive probe with ultrasharp tip (NSC21/Pt, Ultrasharp). For a typical nanoscale welding process, AFM is first changed from tapping mode to contact mode. Then, the feedback function is turned off, so that the distance between the conductive AFM tip and the sample platform can be adjusted. After that, the conductive AFM tip is control to move to the welding position. The tip is brought down to the substrate until the distance between the tip and the substrate is less than 20 nm.

In the process of nano welding, an impulse voltage of -10V is exerted between the AFM tip and the sample surface to produce an induced electric field. The impulse duration is about 300ms. The height of the deposited metal varies with the distance between the AFM tip and the surface of the substrate. Figure 7 shows the process to deposit metal using the method of nanoscale welding. After welding, the metal was deposited from the conductive AFM tip to the surface of the electrode.
B. Nanowelding of SWCNTs

Figure 8 show the AFM height images before and after welding of SWCNTs on the electrodes.

The figure shows that the SWCNTs have been welded on the edges of the electrodes. For a typical CNT-FET shown in Figure 8, the two electrodes are defined as source and drain, SWCNTs act as the channel, and the silicon substrate is regarded as the back gate. Figure 9 show the I-V curves of a typical CNT-FET fabricated by the nano-welding method. The measured I-V curve shows that SWCNTs have not been damaged during the nanowelding process.

V. CONCLUSION

In summary, we have repeatedly demonstrated the welding of SWCNTs to electrodes used AFM tip induced electric field to melt the conductive material on the tip. We have also developed a model to describe the electric field around the conductive tip. The induced electric field will produce field evaporation of metal atoms from the conductive AFM tip. In the process of nanowelding, an impulse voltage of -10V is exerted between the AFM tip and the electrode surface. The impulse duration is about 500ms. The distance between the AFM tip and the sample, the impulse time and the voltage exerted will affect the size of the welding dots.

ACKNOWLEDGMENT

The authors acknowledge the Shenyang National Laboratory for Materials Science for their supply of SWCNTs and the Thirteenth Research Institute, CETC for the fabrication of micro electrodes.

REFERENCES