Experimental Studies of DNA Electrical Properties Using AFM Based Nano-Manipulator

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***Abstract*— DNA molecules adopt many different structures including kinks, bends, bulges and distortions. The different structures and inappropriate physical contacts may result in the controversy of DNA conductivity reported over the last decade. In order to prove this hypothesis, an AFM based experimental method has been developed in this paper. The AFM based nanomanipulation system can be used either as a nanolithography tool to make small-gap electrodes or a nanomanipulation tool to elongate, deform and cut DNA molecules. By measuring the conductivity of DNA molecules in different shapes, it is promising to find conclusive evidences to verify the electrical conductivity of DNA molecules.**

***Index Terms*— DNA Manipulation, DNA Conductivity, AFM, Augmented Reality**

I. Introduction

Recently, DNA molecule has drawn much attention in engineering application because of its appealing features for use in nanotechnology: it's minuscule size, with diameter of about 2.4 nm, its short structural repeat of about 3.4-3.6 nm [1]. The desire to use DNA as the ultimate building blocks of electronic circuits has motivated the study of DNA electrical properties. The initial model for electron transfer through DNA is based on overlapped π-stack orbitals in adjacent base pairs. After much initial controversy over the past 15 years, the mechanisms of charge-transfer are now moving towards a consensus view that the dominant charge-transfer in DNA appears to be distance-dependent coherent tunnelling through unit-step and weak-distance-dependent thermal hopping through multi-step [2]. Both charge-tunnelling and thermal-hopping have been verified in [3].

Contrary to the theoretical consensus, the debating still remains among physics groups due to the disparate experimental results. Some results suggest that DNA is a good conductive molecule wire [4] or even a super conductor in low temperature [5], some report that DNA is a semiconductor [6], [7], while others find that DNA behaves as an insulator [8]. However,

Indeed, the DNA molecule adopts many different structures which may affect the measurement results. These include kinks, bends, bulges and distortions along the molecule. By measuring the height of a single DNA molecule, it has been found that there is very large compression deformation of the deposited DNA on the most common used substrates like mica and silicon oxide surface. In [9], the thickness of DNA molecules on the substrates treated by pentylamine is nearly 2.4 nm comparing to the thickness of 1.1 nm for DNA molecules on clean substrate. Using atomic force microscopy (AFM) in spreading resistance mode, it has been found that the DNA is insulating on clean substrate but conductive on treated substrate. Another significant factor, which may affect the measurement result, perhaps is the electrical contact. Ideally, the contact should be ohmic so that any no-linearity in the conductivity of the molecular wire can be correctly attributed and studied [10]. It has long been recognized that to make good electrical contact between a molecule and a conducting electrode, a chemical bond is required.

In this paper, a series of electrodes with gaps from 100nm to 3um are fabricated to measure the electrical conductivity of single DNA molecules and DNA bundles. The bonding method in [11] is used to guarantee a good contact between the DNA molecule and the electrode. Using AFM based nanomanipulation system, the DNA molecules and bundles can be elongated, deformed and cut. By measuring the electrical conductivity of DNA molecules in different shapes between electrodes with different gaps, conclusive evidences may be found to stop the recent dispute of DNA electrical conductivity.

II. AFM Based Nanomanipulation System

Recently, AFM has rapidly extend its ability from imaging surface in nanoscale to manipulation of nano-objects [12], [13], [14], [15]. The main problem of these manipulation schemes is the lack of real-time visual feed-

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back. Each operation has to be verified by another new image scan before the next operation. Obviously, this scan-design-manipulation-scan cycle is time consuming and makes manipulation inefficient. The Augmented Reality System developed in [16] aims to provide the operator with real-time visual display and force feedback. The real-time visual display is a dynamic AFM image of the operating environment which is locally updated based on real-time force information and system models. Under the assistance of the Augmented Reality System, the operator can perform several operations without the need for a new image scan. The signal flows of the Augmented Reality System are shown in shown in Fig 1.

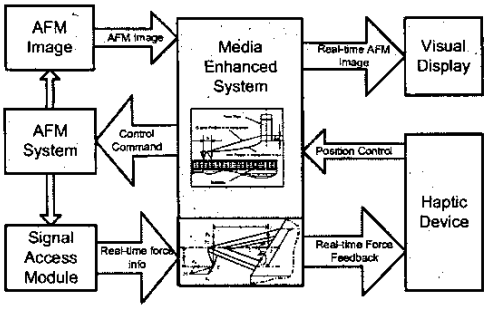


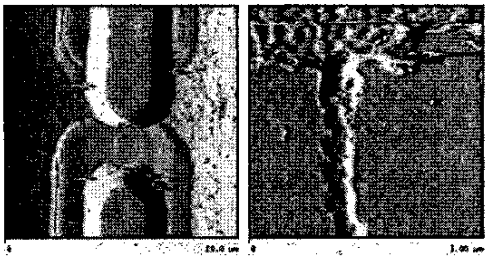
Fig. 1. Nanomanipulation system: The left is the AFM system, which includes other accessories for imaging functions. The middle and right is the Media Enhanced System which provides the operator an augmented reality environment to control the tip motion through a haptic joystick, at the same time view the real-time AFM image and feel the real-time force feedback during manipulation.

The Augmented Reality System has been successfully used to manipulate nano-particles and nano-rods in [17]. In this paper, we extend the ability of the Augmented Reality System to manipulate DNA molecules. Using this system, the DNA molecule shape can be modified by elongating, deforming and cutting. The conductivity of DNA can be measured at its different shapes between the same electrode.

III. Fabrication of Electrodes

In order to verify the distance dependence of DNA conductivity, a series of electrodes with gaps from 100nm to 3um were fabricated on transparent substrates like polycarbonate. The advantages of polycarbonate substrate are its transparency for easily locating the electrodes through an inverted optical microscope, and its softness to protect AFM tip. Another advantage is its hydrophobic surface property, which keeps DNA molecules in their original shape without strong compression due to adhesion force.

We have demonstrated previously in [18] that gold (Au) microelectrodes with gap distances smaller than 2m were fabricated using a 5m gap distance mask design by over-developing technique during image reversal process. Fig.



(a) (b)

Fig. 2. (a). AFM image of the electrodes fabricated on a polycarbonate surface with a gap of 3um (10um scanning range). (b) AFM image of electrodes fabricated by AFM nanolithography on a gold coated polycarbonate surface with a gap of 150nm (5um scanning rang).

2(a) shows a pair of electrode with gap of 3um fabricated by this method. In order to increase the possibility of more DNA molecules lying inside the electrode gap, a wide and short gap is preferred. However, it is very hard to make a gap smaller than 100nm. Fortunately, the AFM itself can also serve as a nanolithography tool under assistance of the augmented reality system. By controlling the AFM tip through a haptic joystick, a very small electrode gap can be made on the gold coated surface. Fig. 2(b) shows that a 150nm gap can be made by inscribing the AFM tip into the gold coated surface (the thickness of gold coating is about 70nm).

IV. Experiments

DNA Samples

In the study of DNA electrical conductivity, most researchers use commercial DNA samples with identical length and identical base-pair sequence such as λ-DNA. However, this may cause problem since DNA has almost unlimited base-pair sequence in nature and the sequence and length may also affect its electrical conductivity. Instead of using commercial DNA sample, raw DNA samples with random length and random base-pair sequence are used in this research. The DNA sample was collected from mature seeds of peony species without restriction (cutting), therefore, some DNA molecules still keep their original length in tens micron (Department of Plant Biology at Michigan State University).

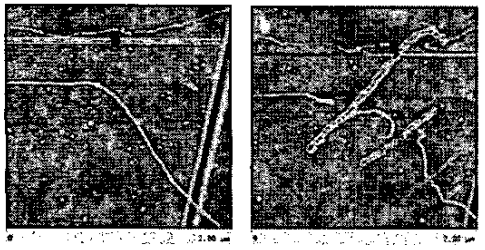
Electrical Conductivity of Bundle DNA

Using the electrodes created by AFM nanolithography methods as shown in Fig. 2(b), conductivity of bundle DNA can be easily measured. The electrodes are connected by a layer of gold 70nm thick (coated by sputtering method). There is linear resistance of 47MΩ between the electrodes before nano-inscribing. After the nano-inscribing, a 150nm gap is created along the connection and the resistance between the electrodes becomes infinite. After the gap has been created, the DNA sample

suspending in DI water was dropped on the electrodes and then blown with dry nitrogen. The resistance between electrodes becomes 500MΩ after depositing DNA sample. This prove that DNA bundles are conductive in short distance. Using the electrodes with 3um gap and similar measurement method, we could not observe the electrical conductivity of DNA bundles in long distance. This experiment partially prove that the conductivity of DNA molecules is distance-dependent.

Manipulation of Single DNA Molecules

In order to compare the electrical conductivity of DNA molecule in its different shape, kinks and deformation of DNA molecules can be created artificially using the AFM based nanomanipulation system. By controlling the pushing force between the tip and sample surface, the DNA molecules or DNA bundles can be either broken or deformed as shown in Fig. 3. A strong pushing force usually break the DNA molecule, and a proper pushing force may only deform DNA molecule without breaking it. In Fig. 3(b), the big scratches on the surface indicate strong pushing force applied on the AFM tip, and small scratches means small pushing force used. We can see that the DNA bundle is broken where a big pushing force applied but only deformed where a small pushing force observed.



(a) (b)

Fig. 3. (a). The AFM image of DNA ropes in its original shape. (b) The DNA ropes are cut by the AFM tip. The pushing force can be controlled in order to cut the DNA rope or only deform the DNA rope. The big scratches on the surface indicate strong pushing force applied, and small scratches means small pushing force used. The arrows indicate the pushing direction

V. Discussions

The recent debate on DNA electrical conductivity requires more efficient experimental methods. We have developed an AFM based augmented reality system, in which the AFM system has been modified into a nanolithography and nanomanipulation tool. Using this system, small-gap electrodes can be made by nanolithography and DNA molecules can be elongated deformed and cut by nanomanipulation. Our next step is to measure the conductivity of DNA molecules in different shapes between electrodes with different gaps. Through cross verification based on a series of experiments, conclusive evidences will be found to terminate the dispute on the electrical conductivity of DNA molecules.

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