Study on the Conductivity of DNA Molecules under Magnetic Fields

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***Abstract*—In this work, the conductivity of DNA molecules under the effect of magnetic fields was studied by conductive atomic force microscopy (C-AFM). It is found that the self-assembly images of 7.5 ng/μL DNA aqueous solution on the bare mica and Au layer surfaces are quite different, and the DNA molecules are obviously stretched on the Au layer surface and single stretched DNA strands were obtained. In addition, the conductivity of single stretched DNA molecules in the horizontal stable magnetic field (SMF) and high frequency electromagnetic field (HEFF) were investigated in detail. The results showed that the conductivity of DNA was weakened by the effect of magnetic field.**

Keywords—DNA molecule, magnetic field, molecular electronics, conductive atomic force microscopy (C-AFM)

I. Introduction

In the past few decades, molecular electronics has attracted great interest. Molecular electronics is the core of nanoscience because it is based on the basic idea that new devices can be created using very small molecules that can produce new characteristics [1]. Molecular electronics has the potential to further design miniaturized devices, have the new functions of molecules as electronic devices [2-6] and the possibility of bottom-up assembly of complex electroactive structures. For molecular electronics to be a future technology, basic research will be crucial [7].

Nowadays, DNA molecules have attracted more attention in the field of nanotechnology for its unique structural and biophysical properties [8]. Owning to the special double-helix structure with π-electron cores of well-stacking bases, DNA molecule may be a good candidate for long distance charge transport [19]. The magnetic field (MF) is a common physical field in our life [9]. It is reported that the magnetic field does affect the physiological characteristics of living cells [10,11], organisms [12] and even DNA molecules to a certain extent, which has aroused widespread interest in the scientific community [13]. In our previous studies, the change of self-assembly behavior of DNA molecules under a magnetic field has been confirmed [14]. However, as a good conductive biomaterial, whether the conductivity of DNA under magnetic fields will be affected has not been clearly studied.

In this work, the conductivity of DNA molecules under the effect of magnetic fields was studied by conductive atomic force microscopy (C-AFM). As a preliminary experiment, the effects of different substrates on DNA self-assembly were investigated in detail. The results show that the surface roughness of Au modified mica was increased, which was conducive to the stretching of DNA molecules, and single stretched DNA strands were obtained. In addition, in both the horizontal stable magnetic field and high frequency electromagnetic field, the conductivity of single stretched DNA molecules was weakened. This study will help to understand the effect of magnetic field on the conductivity of DNA molecules and enhance the cognition of DNA application in the field of biophysical technology.

II. Method and Experiment

A. Materials

The λ-DNA stock solution (500 ng/μL) was purchased for this experiment. The mica square sheets (1.0×1.0 cm^2) were all freshly cleaved. The ultrapure water (⩾18.2 MΩ·cm) was purified with a Milli-Q water purification system.

B. Preparation of DNA solution

In this work, 7.5 ng/μL DNA solution was prepared by diluting the DNA stock solution with ultrapure water.

C. Preparation of Au layer on mica surface

In this work, the Au layer was prepared as the conductive layer applied on the detection of DNA conductivity under the effect of magnetic field. A sputtering system (Q150TES, Quorum Technologies Ltd) was used to prepare the Au layer (20 nm) on the freshly cleaved mica surface as shown in Figures 1a and 1b.

D. Atomic force microscopy measurements

In this work, two types of AFM instruments including Agilent AFM and JPK AFM were utilized for the AFM test. The Agilent Technologies 5500 Scanning Probe Microscope (SPM) was used to preliminarily investigate the morphologies of DNA and substrate before and after the substrate modified with an Au layer. The prob used in the tapping mode was Tap300Al-G. The resonant frequency was typically set to 200 ~ 400 kHz. For a detailed study on the conductivity of DNA affected by the magnetic field, the JPK AFM (NanoWizard®3) with the conductive module C-AFM under the contact mode was used. The probe used in this section was a SCM-PIC-V2 conductive probe, and it was used to detect the current under the DC voltage set from -10 V to +10 V. The spring constant of the probe was 0.1 N/m.

It was important to recognize that all the above tests were performed at room temperature.

E. DNA conductivity measurement under magnetic fields

Figure 1 displays the schematic drawing of DNA conductivity affected by magnetic field and measured by C-AFM. In brief, the conductive probe and the Au layer constructed two electrodes connecting the DNA molecule, respectively. At the same time, the static magnetic field (SMF) and high frequency electromagnetic field (HFEF) acting on DNA samples were constructed respectively. The intensities of the two types of magnetic fields were adjusted by an E363A instrument. The intensity and frequency of the HFEF were adjusted by AFG3022C dual channel arbitrary/function generator (Tektronix Company, USA). In this paper, the intensity of the magnetic fields was expressed by the magnitude of the output voltage. In this work, the directions of the two types of magnetic fields were all parallel to the substrate surface.

F. Contact angle test

The Drop Shape Analyzer-DSA100 was applied for the contact angle test in this work.

G. Statistical analysis

Through the investigation of at least five groups of independent experiments, the AFM images were obtained.

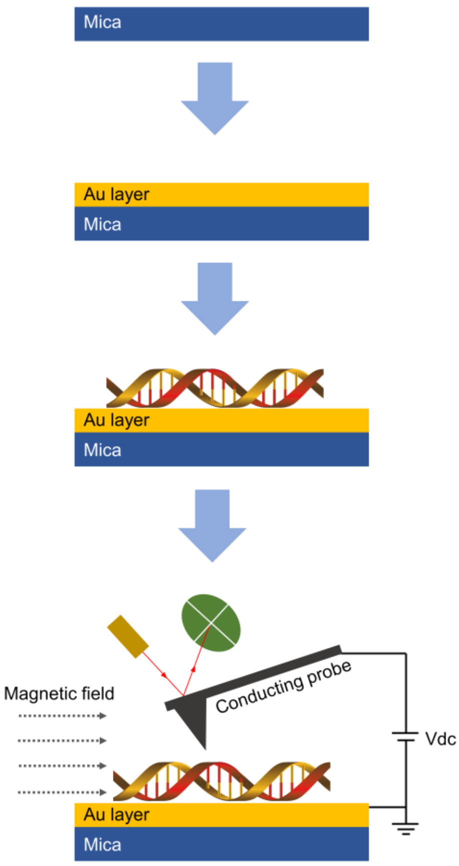

Figure 1 The schematic diagram of DNA conductivity under the effects of magnetic fields measured by C-AFM.

III. Results and Discussion

In order to know the influence of substrate surface characteristics on the DNA sample preparation, the DNA samples on the mica surface and Au layer surface were prepared respectively, as shown in Figure 2. It can be clearly seen the difference of DNA molecule assembly on the bare mica surface as well as the Au layer surface. As shown in Figure 2a, the DNA molecules exhibit a network structure. In contract, the DNA molecules on the Au layer assembled into parallel lines (Figure 2b), which were different from the patterns on the bare mica surface. It should be noticed that, the height of DNA patterns is increased obviously on the Au layer. While the height of DNA strands in Figure 2b is increased significantly to reach 20 nm, which is almost 40 dsDNA high. Remarkably, in addition to the taller DNA strands, the individual DNA strands could also be found in the AFM image, which are also stretched and arranged parallel to each other. These results show that the deposition of Au layer on the mica surface is an important factor affecting the DNA self-assembly since it can change the self-assembly morphology of DNA samples and further affect the conductivity of DNA samples.

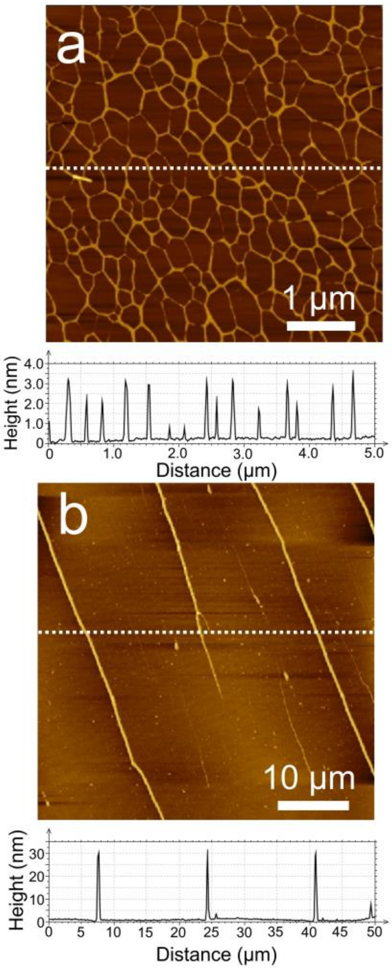

Figure 2 The AFM morphological images of DNA molecules deposited on (a) bare mica and (b) Au layer surfaces. Below the morphological images are their corresponding height profiles. The DNA molecules were stretched on the Au layer surface.

There is no doubt that in the above self-assembly process of DNA molecules, the DNA molecules are subjected to a variety of different forces [15-18]. In order to explain the above different results of DNA self-assembly caused by different substrate modifications, the morphology, roughness, hydrophilicity and hydrophobicity of bare mica and gold layer surfaces were carefully tested, as shown in Figure 3. It can be seen from Figures 3a and 3b that the morphologies of the bare mica and Au layer surfaces are obviously different. The surface of bare mica is flat without obvious bulge, while the particles with the height of tens of nanometers can be clearly found on the surface of the Au layer.

By analyzing the height, the roughness of the two types of surfaces were obtained, which were 0.0825 nm and 7.03 nm, respectively. On the one hand, the increase of surface roughness increases the chance of DNA molecules contacting with the substrate surface. On the other hand, it can be seen from Figures 3c and 3d that the increase of surface roughness reduces the surface hydrophilicity, which makes it difficult for the DNA droplet to diffuse on the Au layer surface. The combination of the two functions makes DNA molecules more vulnerable to the action of molecular comb in the drying process, and finally resulting in the stretching of DNA molecules.

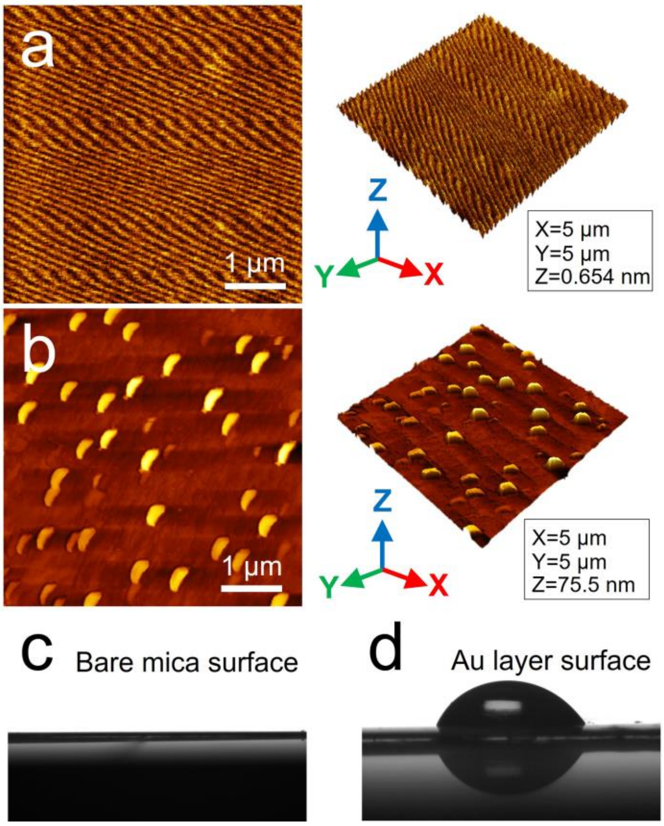

Figure 3 The AFM images, 3D topographic maps of (a) bare mica and (b) Au layer surfaces. Pictures c and d are the water droplet on the bare mica surface and Au layer surface, respectively.

Figure 4 shows the morphological and current images of the stretched DNA strand on the surface of the Au layer tested by the C-AFM module under the -10 V DC voltage. The height of the DNA strand is measured to be about 0.5 nm, as shown in the corresponding height profile of Figure 4a, which is the height of double stranded DNA. In addition, it can be seen that when a negative electric field is applied to the DNA sample, the current reflected on the DNA sample is also negative compared with the positive current of the substrate.

In this work, two types of magnetic fields (SMF and HFEF) were applied respectively on the DNA strands for the investigation of the conductivity of DNA molecules under magnetic fields. For detailed discussions, the current intensity flowing through the DNA strand was measured by C-AFM by changing the intensity or frequency of the magnetic field, as shown in Figure 5.

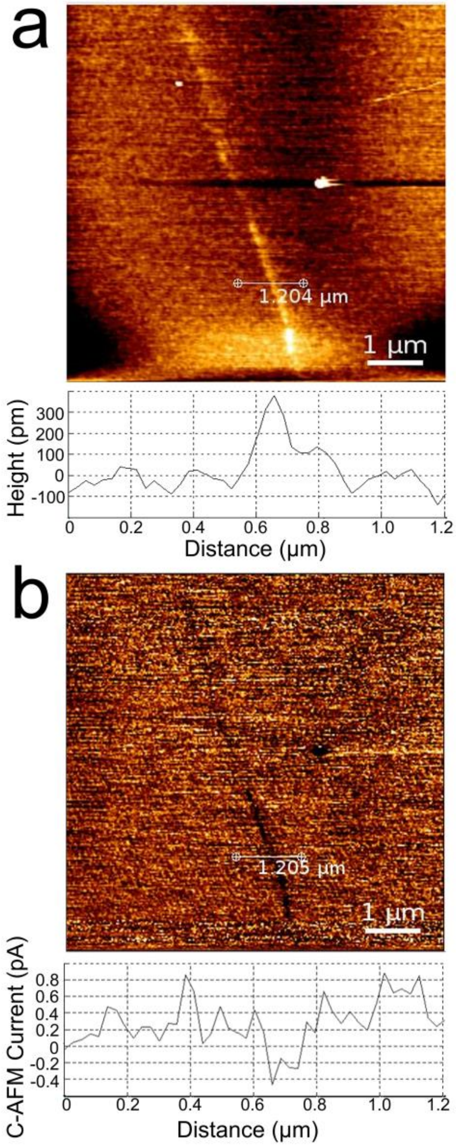

Figure 4 The morphological (a) and current (b) images of DNA strand on the Au layer surface tested by C-AFM without the effect of magnetic field. The line charts are the corresponding height and current profiles, respectively.

Figure 5a shows the conductivity of DNA strands under the action of SMF with different intensities. Under the negative bias voltage, the current flowing through the DNA strands is also negative no matter whether the magnetic field is applied or not. Without the application of magnetic field, the current is measured to be -4.38 pA. When 6 V SMF is applied, the current intensity is decreased to -1.45 pA. At 25 V SMF, the current intensity is increased slightly to -3.01 pA.

Figures 5b and 5c show the conductivity of DNA strands under the action of HFEF with different frequencies and the HFEF intensities of 5 V and 10 V, respectively. The current values are -2.94 and -3.23 pA at the frequency of 10 and 25 MHz when the HFEF intensity is 5 V. While as the frequency is increased to 10 MHz, the current values are measured to be -1.43, -1.21, -2.09 and -2.14 pA at the frequency of 10, 15, 20 and 25 MHz. It can be seen from the above results that compared with the controlled experiment, with the increase of frequency, the current flowing through the DNA strands presents that it has a decrease first and then has a increase tendency. Thus, the conductivity of DNA molecules could be influenced by magnetic fields.

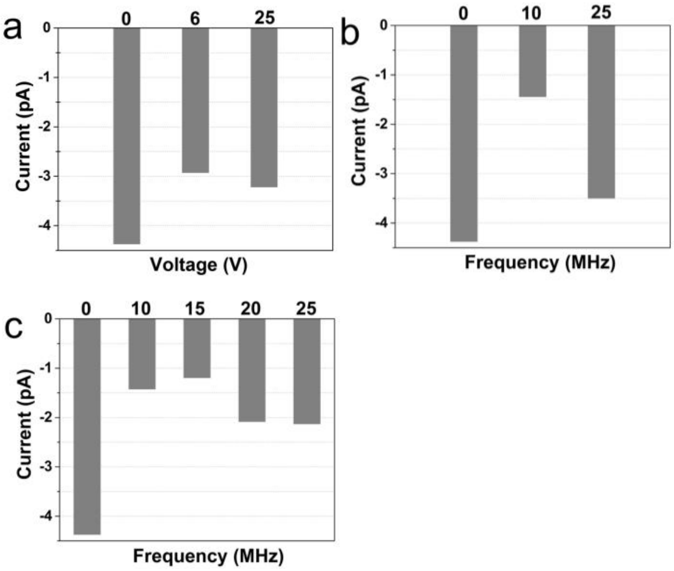

Figure 5 (a) Current distributions of DNA strands under the effect of SMF with different intensities (0 V, 6 V and 25 V). (b) Current distributions of DNA strands under the effect of 5 V HFEF with different frequencies (0, 10 and 25 MHz). (c) Current distributions of DNA strands under the effect of 10 V HFEF with different frequencies (0, 10, 15, 20 and 25 MHz).

IV. CONCLUSION

In this work, the conductivity of DNA molecules subjected to effect of magnetic fields was studied by conductive atomic force microscopy (C-AFM). The results reflected that the self-assembly images of DNA on the bare mica surface and Au layer surface were quite different. The DNA molecules are obviously stretched on the Au layer surface and single stretched DNA strands were obtained. In addition, the conductivity of single stretched DNA molecules in the horizontal stable magnetic field (SMF) and high frequency electromagnetic field (HFEF) were investigated in detail. The results showed that the conductivity of DNA was weakened by the effect of magnetic field. This study will help to understand the effect of magnetic field on the conductivity of DNA molecules and enhance the cognition of DNA application in the field of biophysical technology

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