RAPID TRANSLOCATION OF DNA MOLECULES THROUGH GRAPHENE
NANOGAPS

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science in Physics

By

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Table of Contents

Copyright ........................................................................................................ i
Signature Page ................................................................................................. ii
Acknowledgements ........................................................................................ iv
List of Tables .................................................................................................... vi
List of Figures .................................................................................................. vii
Abstract .......................................................................................................... ix

1 Introduction 1
  1.1 Deoxyribonucleic acid (DNA) .............................................................. 1
  1.2 Nanopores and Nanogaps ................................................................. 2
  1.3 Graphene .......................................................................................... 5
  1.4 Atomic Force Microscope (AFM) ....................................................... 6
  1.5 Electron Beam Lithography (EBL) ..................................................... 6
  1.6 Project Outline ................................................................................. 8

2 Materials and Methods 9
  2.1 Acquiring Graphene ........................................................................ 9
  2.2 Determining Thickness of Graphene With AFM ......................... 10
  2.3 Trench Sample Preparation ............................................................. 11
  2.4 Graphene Transfer .......................................................................... 12
  2.5 Translocation Measurements .......................................................... 14

3 Results 16
  3.1 Stability of Current ......................................................................... 16
  3.2 Nanogap Conductance .................................................................... 17
  3.3 DNA Translocation ........................................................................ 19

4 Discussion 21

5 Conclusion and Outlook 25

References 26
List of Tables

4.1 Comparison of DNA translocation through graphene nanopore results (6, 23, 24) with the results of DNA translocation through graphene nanogaps…………………………………22
List of Figures

1.1 DNA structure overview; Chemical structure of DNA sequences: two ring structure (purines) Guanine, Adenine and one ring structure (pyrimidines) Thymine, Cytosine and Sugar-Phosphate backbone. [Figure from (2)] .....................................................................................2
1.2 (a) Ion current versus time plot; before DNA enters a nanopore, DNA inside a pore and DNA after translocating through a nanopore, (b) Comparison of membrane thickness of 20 nm SiN and single layer graphene when used for DNA translocation through a nanopore. [Figure reproduced from (6)].........................................................4
1.3 Atomic structure of graphene. [Figure from (22)].........................................................5
1.5 (a) Schematic view of an Atomic Force Microscope [figure from (28)], (b) Schematic view of an EBL system [figure from (29)]: a wafer handling system automatically feeds wafers to the system and a mechanical stage positions the wafer under the electron beam. Once an electron gun supplies the electrons, an electron column shapes and focuses the electron beam. A beam of electrons is then scanned in a patterned fashion across the surface covered with a resist.............................................................................................................7
2.1 Optical image of graphene with one, two, three, and four layers.................................10
2.2 (a) Close contact mode AFM image of graphene edge of thickness 0.3 ± 1 nm, (b) Profile line is drawn in red color and the measured thickness is 1.27 nm........................................................................................................................................10
2.3 (a) Optical image of a marker sample after EBL and gold deposition, and (b) Optical image of a trench sample........................................................................................................................................12
2.4 Schematic view of the wedging technique and graphene breakage: (a) CAB-immobilized graphene, (b) Nitrogen plasma on the substrate, (c) Hydrophobic repulsion, (d) Positioning a graphene flake on a trench sample, (e) Graphene flake on a trench sample with CAB on it, (f) Dissolution of polymer support and breakage of graphene, (g) PMMA-immobilized graphene, (h) Micropore in PMMA using electron gun, (i) Hydrophobic repulsion, (j) Positioning on a target device, (k) Graphene nanogap device ready for measurements........................................................................................................................................13
2.5 The tested devices are: (a) Micropore in PMMA on a gold template, (b) Graphene nanogap on a target device (50 µm hole in SiN), (c) Graphene nanogap on a target device (5 µm hole in SiN), (d) Micropore in PMMA on a trench sample. Image (e) shows the graphene nanogap device in a flow cell with ionic solution. Image (f) shows the setup for ion current and DNA translocation studies........................................................................................................................................15
3.1 (a) Unstable ion current without polymer, (b) Stable ion current after using PMMA........................................................................................................................................16
3.2 Linearity of the I-V curve indicates that the current is consistent with ion flow through the gap and does not arise from electrochemical processes at the conductive graphene surface. (a) Conductance-13 nS, resistance-70 MΩ, (b) Conductance-800 nS, resistance-1 MΩ, (c) Conductance-8 nS, resistance-100 MΩ, and (d) Conductance-9000 nS, resistance-100 KΩ, (e) Nanogap blockade conductance versus event duration during DNA translocation........................................................................................................................................18
3.3 Translocation events of 48 kbp double-stranded λ-DNA through a nanogap: (a) Long event with low ion current, (b and c) Short events with high ion currents, (d) Long event with high ion current due to graphene-DNA interactions.........................................................19
List of Figures Continued

4.1 Plots for the results shown in table 4.1; (a) Conductance blockade, \( \Delta G \) versus KCl concentration, \( C \), (b) Velocity, \( v \) versus \( V^2 \)………………………………………………………………………………23
ABSTRACT

RAPID TRANSLOCATION OF DNA MOLECULES THROUGH GRAPHENE NANOGAPS

By

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Master of Science in Physics

A nanogap is a small slit in a continuous impermeable membrane which may be used for active and passive transport of biological molecules. Biological nanopores and solid-state nanopores currently have limitations; however, graphene provides an ideal platform for biomolecule counting and characterization. Nanogaps fabricated in single layer graphene may give single base resolution that may enable DNA sequencing. Graphene flakes are produced by exfoliation and measured by close contact mode atomic force microscopy to determine the thickness of flakes and 150 nm deep, 2 μm wide trenches in SiO₂ have been used to create a nanogap. The nanogap is measured in 0.1M KCl ionic solution, as individual DNA molecules translocate through the gap, characteristic conductance changes are observed in the ionic current through the nanogap. DNA translocation through several devices has been studied and it appears that the conductance blockade, ΔG follows the same trend as graphene nanopore devices. In the context of graphene nanogaps, this thesis serves as a characterization of graphene nanogaps that is useful for future genome screening.
Chapter 1

Introduction

1.1 Deoxyribonucleic acid (DNA)

Deoxyribonucleic acid (DNA) is a nucleic acid containing the genetic instructions used in the development and functioning of all known living organisms. In 1951, DNA was first investigated by X-ray diffraction, leading to the discovery of the double helix structure by James Watson and Francis Crick in 1953. The atomic structures of each DNA base and backbone of the DNA are shown in figure 1.1. The DNA strand is stabilized with a backbone structure and the bases are attached horizontally to it. The DNA backbone is a polymer with an alternating sugar-phosphate sequence, and the monomer units of DNA are nucleotides while the polymer is known as a “polynucleotide.” Each nucleotide consists of a 5-carbon sugar, a nitrogen containing base attached to the sugar, and a phosphate group. The four nucleotides are given one letter abbreviations: A for adenine, G for guanine, C for cytosine, and T for thymine. These four bases are divided into two categories based on the structures; purines have two ring structures (adenine and guanine) while pyrimidines have one ring (thymine and cytosine). The double helix DNA molecule is held together by two forces, hydrogen bonding between base pairs and base-stacking interactions. The double stranded DNA (dsDNA) chain is 2.2-2.6 nm wide and nucleotides are 0.33 nm apart along the backbone (1), while the single stranded DNA (ssDNA) chain is 1.1-1.3 nm wide. These values are also the theoretically expected height of DNA on a surface. In this research project, dsDNA was used for the translocation studies.
Figure 1.1: DNA structure overview; Chemical structure of DNA sequences: two ring structure (purines) Guanine, Adenine and one ring structure (pyrimidines) Thymine, Cytosine and Sugar-Phosphate backbone. [Figure from (2)]

1.2 Nanopores and Nanogaps

A nanogap is a small slit in a continuous impermeable membrane. In nature, membranous proteins with nanopores are used by cells for active and passive transport of biomolecules and ions. Though very useful in nature, they have also recently been applied by scientists for monitoring the translocation of biological molecules through a self-assembled membrane barrier. A single polymer molecule can travel through a nanopore of several nanometers across. This molecule can be studied while it travels through the nanopore, which is typically done by allowing an ionic solution to flow through the nanopore. A molecule translocating through the nanopore blocks a portion of
the ionic current depending on the diameter of the molecule. An example of this procedure is the translocation of DNA.

There are mainly two fundamental methods researchers have implemented to study DNA translocation; biological nanopores and solid-state nanopores. In the case of biological nanopores, the protein, alpha-hemolysin is employed as a lytic agent by flesh eating bacteria since it effectively pokes holes in cell membranes (3). At its narrowest point, alpha hemolysin is a pore just over a nanometer in diameter which allows a constant transport of ions with an applied bias and also allows the serial transport of single stranded DNA. However, once DNA is inserted, it effectively clogs up the pore which blocks the ion transport. Figure 1.2 (a) shows steady ion current before inserting DNA, ion current blockade during the DNA translocation and baseline current after DNA has translocated through a nanopore. By monitoring the characteristic drop in ionic current due to this blockage, the presence of translocated DNA through the pore is detected, thus enabling the counting of biomolecules. Biological nanopores are stable in a small range of chemical environments, pH value, temperature, and applied electric fields (4).

Solid-state nanopores can be fabricated from Si, SiN, SiO\textsubscript{2} (5) and they are more robust than the self-assembled membranous system. However, a typical thickness of solid-state membrane is 20 nm, meaning there may be 10-100 base pairs present in the nanopore at a given time, which is an imminent obstacle for DNA sequencing. In order to detect base pairs individually, a thinner membrane is required. A candidate material which would lead to highly efficient sequencing is a single atom thick membrane of
graphene due to its properties discussed in section 1.3. The difference in thickness of the graphene membrane compared to a 20 nm SiN membrane is illustrated in figure 1.2 (b).

Figure 1.2: (a) Ion current versus time plot; before DNA enters a nanopore, DNA inside a pore and DNA after translocating through a nanopore, (b) Comparison of membrane thickness of 20 nm SiN and single layer graphene when used for DNA translocation through a nanopore. [Figure reproduced from (6)]

DNA consists of base pairs that are known to have characteristically distinctive properties. By taking transverse conductance measurements, it may be possible to determine the sequence of DNA. If a nanopore is employed for such measurements, electrons are free to go around the nanopore, leading to the possibility of misidentifying a sequence. However, if a nanogap is used, it is possible to overcome this misidentification. Although the theory is present, experimental results are yet to confirm this. In this thesis, I present experimental demonstration of dsDNA translocating through graphene nanogap, which represents a milestone towards graphene nanogap sequencing.
1.3 Graphene

In recent years graphene has been widely researched as it promises to be a useful material in many research fields (21). The atomic structure of graphene is shown in figure 1.3. Graphene is a one-atom-thick 2D crystal-like structure of carbon atoms arranged in a hexagonal lattice (7, 8) where the charge carriers are massless Dirac fermions (9, 10, and 11). Graphene is the world’s thinnest and strongest material (12). Graphene is electrically and thermally very conductive (13, 14), very elastic, and impermeable to any molecules (15). Graphene can be produced by micromechanical cleavage (7, 8) and a Chemical Vapor Deposition (CVD) method (16, 17, 18, and 19) and transferred onto any devices. Graphene is considered a very attractive material for both fundamental physics studies and potential applications. Graphene has a thickness of only 0.3 nm (20) which makes it an ideal candidate for the sequencing of DNA with nanogaps because graphene not only helps obtain electrical measurements, but also gives single base resolution.

Figure 1.3: Atomic structure of graphene. [Figure from (22)]

The first theoretical paper published on the rapid sequencing of DNA molecules through graphene nanogaps emerged from the Postma group of California State University, Northridge (CSUN) (4).
Three experimental papers published on DNA translocation through graphene nanopore came out from a group of TU Delft (6), a group of University of Pennsylvania (23) and a group of Harvard University (24) with the reported conductance blockade, $\Delta G$ value of 1.5 nS, 4.5 nS and 8.1 nS respectively. The meaning of conductance blockade, $\Delta G$ is further explained in section 3.2 and the comparison of results is shown further in section 4.

1.4 Atomic Force Microscope (AFM)

The Atomic Force Microscope (AFM) is a scanning probe microscope which is used for mapping and measuring surface features of extremely small objects - from a carbon atom that is 0.25 nm or 2.5 Å in diameter to the cross section of a human hair (approximately 80 µm in diameter). A schematic view of an AFM is shown in figure 1.5 (a). A very sharp tip attached to a cantilever is dragged across a sample surface and the change in the vertical position (denoted the "z" axis) reflects the topography of the surface. The tip deflection is determined from a laser reflection off the cantilever into a photo diode. By collecting the height data for a succession of lines, it is possible to form a three dimensional map of the surface features. The AFM has a high resolution in the vertical direction (0.1 nm) and a slightly lower resolution in the lateral direction (1 nm) (25). In this research, an AFM has been used to determine the thickness of graphene flakes.

1.5 Electron Beam Lithography (EBL)

Electron Beam Lithography (EBL) is the technique commonly known for scanning a beam of electrons in a patterned fashion across a surface covered with a resist. The schematic of a typical EBL system is shown in the figure 1.5 (b). Electron beam resists
are the recording and transfer media for electron beam lithography. EBL has the advantage of being able to overcome the diffraction limit of light and make features in the nanometer regime. The final pattern is created from a digital representation on a computer, by controlling an electron beam as it scans across a resist-coated substrate. There are two forms of EBL resists—negative tone and positive tone. Positive tone resists are developed away at exposed regions and the developed region remains after development in case of negative resists (26, 27). A positive resist Polymethyl methacrylate (PMMA) has been used and trenches have been fabricated in SiO₂ using EBL for this research.

Figure 1.5: (a) Schematic view of an Atomic Force Microscope [figure from (28)], (b) Schematic view of an EBL system [figure from (29)]: a wafer handling system automatically feeds wafers to the system and a mechanical stage positions the wafer under the electron beam. Once an electron gun supplies the electrons, an electron column shapes and focuses the electron beam. A beam of electrons is then scanned in a patterned fashion across the surface covered with a resist.
1.6 Project Outline

The purpose of this thesis is to characterize graphene nanogaps by counting the individual DNA molecules as they pass through the nanogap and by monitoring the translocation time of the events as well as the event amplitude. A description of the fabrication procedure is provided in chapter 2 and the results are presented in chapter 3.
Chapter 2
Materials and Methods

2.1 Acquiring Graphene

Researchers have used two methods of acquiring graphene, mechanical exfoliation and CVD. For this research the mechanical exfoliation method is used to produce graphene. A 5-10 mm piece of a graphenium flake (manufacturer: NGS Naturgraphit GmbH) is placed on blue Nitto tape (manufacturer: Nitto denko, SPV 224LB-PE). The tape is folded and pulled apart several times in order to cover the tape with graphene. Due to its optimal value for optical contrast in white light for graphene on SiO$_2$ wafers, a wafer with a thermally grown 285 nm SiO$_2$ layer is used (30). SiO$_2$ is cleaned with water, Iso-Propanol Alcohol (IPA), acetone, and ethanol. This wafer is placed in a plasma cleaner and is exposed to oxygen plasma for 5 minutes in order to make it hydrophilic. This wafer is then placed on a blue tape strip (Nitto tape), covered with graphene and then pressed against the tape in order to adhere the graphene on the SiO$_2$ surface. The wafer, with varying thicknesses of graphene, is examined under an optical microscope. Graphene flake thicknesses are distinguished by the color contrast observed by the microscope, thus, it is possible to estimate the thickness of a graphene flake based on the familiarity with the overlapping color regions. An overview of different colors and thicknesses of a graphene flake is shown in figure 2.1. Optical images of a chosen flake are taken at different magnifications (5x-100x).
2.2 Determining Thickness of Graphene With Atomic Force Microscope

Once the flake is selected, the thickness is measured using an AFM in close contact mode to determine the height of the flake.

![AFM Image and Height Profile](image)

Figure 2.2: (a) Close contact mode AFM image of graphene edge of thickness 0.3 ± 1nm, (b) Profile line is drawn in red color and the measured thickness is 1.27 nm.

The image data is analyzed by the SPM cockpit software program. The AFM image of a graphene flake is shown in figure 2.2 (a) and the height profile is shown in figure 2.2 (b). There are reports on the uncertainty of thickness measurement of graphene with
AFM. For single layer graphene, up to 1 nm has been measured instead of 0.3 nm (20). It is safe to consider an error margin of 1 nm on the thickness of graphene flake because the errors found in this experiment are consistent when observing the different profile lines.

2.3 Trench Sample Preparations

The trenches of 150 nm deep and 2 um wide are created in SiO$_2$ using EBL. A SiO$_2$ wafer is diced using a diamond knife to obtain 1.5×1.5 cm$^2$ sample, which makes the wafer easier to handle. The wafer is then cleaned with water, Iso-Propanol Alcohol (IPA), acetone, and ethanol. It is then pre-baked for 30 minutes at 150°C and PMAA is spin coated at 4,000 rpm for 1 minute. It is then post baked at 150°C for 5 minutes. The pattern is designed using QCAD program and the sample is then placed in the SEM for EBL. After EBL, the patterned sample is developed with 1:3-MIBK: IPA for 1 minute. Hydrofluoric etch is done on the sample for 30 seconds to etch oxide from the exposed area. It is examined with an optical microscope and placed in an evaporator for Cr deposition of 4 nm, followed by deposition of 30 nm of gold. Acetone is used to liftoff excess gold by dissolving the PMMA from the sample. An optical image of a marker sample is shown in figure 2.3 (a). The sample is then spin coated with PMAA for 1 minute at 4,000 rpm and baked at 150°C for 5 minutes. The trenches are patterned on the sample, it is developed with MIBK: IPA for 1 minute. A hydrofluoric etch is applied to the sample for 30-60 seconds in order to etch 120-150 nm of oxide from the wafer. PMAA is removed from the sample with acetone. An optical image of the trench sample is shown in figure 2.3 (b).
2.4 Graphene Transfer

The wedging transfer technique is used to transfer graphene flakes from one substrate to another and position it with ~ μm accuracy (31). This technique makes use of an interface between a hydrophilic and a hydrophobic surface. Hydrophobic molecules are nonpolar molecules and tend to stay away from polar molecules (hydrophilic molecules). In this method, the capillary forces cause the water to invade the hydrophilic/hydrophobic interface and separate the surfaces. Once a proper graphene flake is found and a trench sample is prepared, the graphene flake is transferred onto a trench sample. The flake is covered with 1.2g/40mL CAB (Cellulose Acetate Butyrate) polymer in ethyl acetate as a transferring polymer. The wafer is placed in a plasma cleaner and exposed to oxygen plasma for 30 s and then dipped in water at an angle of about 30°. At this angle, the water begins encroaching underneath the polymer, detaching the polymer with graphene flake from the water, and allowing it to float on the water surface. A micrometer screw is used to position the flake onto the trench sample which is done under the optical microscope. The water is removed in order for the flake to attach itself to the trench sample. The sample is placed on a hot plate at 80°C to dry and the CAB is then dissolved with ethyl
acetate in the last step. After dissolving CAB, the sample is placed in IPA for 1 minute. In the drying process, the capillary forces cause the graphene to break. A schematic view of the wedging transfer procedure and graphene breakage is shown in figure 2.4 (a) to 2.4 (k). For some of the devices, graphene flake is transferred onto a target device (5 µm hole through SiN) after step 2.4 (f), for some of the devices all the steps 2.4 (a) to 2.4 (k) are followed as discussed further in section 3.1.

Figure 2.4: Schematic view of the wedging technique and graphene breakage: (a) CAB-immobilized graphene, (b) Nitrogen plasma on the substrate, (c) Hydrophobic repulsion, (d) Positioning a graphene flake on a trench sample, (e) Graphene flake on a trench sample with CAB on it, (f) Dissolution of polymer support and breakage of graphene, (g) PMMA-immobilized graphene, (h) Micropore in PMMA using electron gun, (i) Hydrophobic repulsion, (j) Positioning on a target device, (k) Graphene nanogap device ready for measurements.
2.5 Translocation Measurements

The tested devices are shown in figure 2.5 (a)-2.5 (d). The nanogap device is mounted in a microfluidic PMMA flow cell. The schematic view of a graphene nanogap device in a flow cell with ionic solution is shown in figure 2.5 (e). The flow cell is made out of two chambers that are joined together with the nanogap device sandwiched between them. The flow cell is then filled with 0.1 M saline solution (10 Mm Tris, 1mM EDTA and 1M KCl at room temperature, pH 8.0). The flow cell has small channels to and from the chambers on both sides. These channels are used for flushing the buffer solution in the flow cell and place the Ag/AgCl electrodes in the solution. The figure 2.5 (f) shows the setup for ion current and DNA translocation studies. The Ag/AgCl electrodes are used to apply electric field across the nanogap, which generates an ion current. Upon adding DNA on one side of the flow cell, by applying a voltage, due to the negatively charged backbone, the DNA translocates through the nanogap towards the other side (positive chamber). By monitoring the ionic current, characteristic drops in current represent the translocation of DNA through the gap, enabling the counting of biomolecules. During the translocation events, two parameters are generally monitored: the time of the translocation event and the conductance blockade, ΔG. DNA can translocate through a nanogap in folded or unfolded fashion (6). In a folded state, two pieces of the strand of DNA go through the gap at the same time; multiple folds may also possible. Typical translocation events of λ-DNA are shown in figure 3.3.
Figure 2.5: The tested devices are: (a) Micropore in PMMA on a gold template, (b) Graphene nanogap on a target device (50 µm hole in SiN), (c) Graphene nanogap on a target device (5 µm hole in SiN), (d) Micropore in PMMA on a trench sample. Image (e) shows the graphene nanogap device in a flow cell with ionic solution. Image (f) shows the setup for ion current and DNA translocation studies.
Chapter 3

Results

3.1 Stability of Current

It is important to have stable ion current in order to accurately count biomolecules passing through a nanogap. During some of the measurements, unstable ion current was observed as shown in figure 3.1 (a). In this experiment, graphene is a freestanding membrane, so during the DNA translocations, the nanogap takes longer to open and permit DNA to pass through. Consequently, this impedes the baseline current to return to its original value, thus leading to an unstable ion current.

![Figure 3.1](image)

Figure 3.1: (a) Unstable ion current without polymer, (b) Stable ion current after using PMMA.

Upon careful observations, it had been proposed that the ion current can be stabilized using a polymer on a graphene flake. The movement of the graphene flake would be more stable with the polymer which would lead to a relative stable ion current.

The initial procedure remained the same as described in section 2.1-2.4 but the final procedure had been modified. After dissolving CAB from a trench sample, the graphene flake is covered with PMMA and baked at 150°C for 15 minutes. A micropore is
fabricated in PMMA directly above the graphene breakage using EBL. The PMMA flake is then transferred onto a target device. For this method, a 500 µm hole through SiN is used as a target device. The ion current is stabilized using a polymer PMMA which reduces stress on the graphene flake and makes the graphene gap relatively stable. Figure 3.1 (b) shows the stable ion current with PMMA onto a graphene flake.

3.2 Nanogap Conductance

For each graphene nanogap, a current-voltage (I-V) curve was obtained and the conductance has been read directly from the plot. All the measurements were done in TE, 0.1 M KCl. Figure 3.2 (a)-3.2 (d) shows various I-V plots for various tested devices. The resistance is of the order of MΩ as expected and the linearity of the I-V plots indicate that there is no electrochemistry arising at the conducting graphene surface. During the translocation of DNA, conductance blockade, ∆G as well as time duration of events was monitored. The conductance blockade, ∆G is a deviation of the baseline conductance when a biomolecule goes through the nanogap, which is a measure of the blockade due to the DNA. The plot of nanogap blockage conductance versus event duration during DNA translocation is shown in figure 3.2 (e). Shorter events have higher blockade conductance as expected. The plot is consistent with an exponential decay approximately, however, we have not been able to confirm this more precisely.
Figure 3.2: Linearity of the I-V curve indicates that the current is consistent with ion flow through the gap and does not arise from electrochemical processes at the conductive graphene surface. (a) Conductance-13 nS, resistance-70 MΩ, (b) Conductance-800 nS, resistance-1 MΩ, (c) Conductance-8 nS, resistance-100 MΩ, and (d) Conductance-9000 nS, resistance-100 KΩ, (e) Nanogap blockade conductance versus event duration during DNA translocation.
3.3 DNA Translocation

Several devices were prepared to study DNA translocation, but not all of them provided adequate translocation. Some devices were either wide open, completely closed, or were immediately clogged up upon adding DNA. Due to graphene-DNA interaction, these devices tend to get clogged more often in comparison to SiN devices. For an applied bias of 39 mV, the relatively fast translocation rate of 20ns/base was observed which minimizes the diffusion. Translocation events of 48 kbp double-stranded λ-DNA through a graphene nanogap are shown in the figure 3.3.

Figure 3.3: Translocation events of 48 kbp double-stranded λ-DNA through a nanogap: (a) Long event with low ion current, (b and c) Short events with high ion currents, (d) Long event with high ion current due to graphene-DNA interactions.
Unfolded events were found to have long event times of about 1.4 ms, and the blockade conductance of about 55 pA. Folded events had short event time of about 0.3-0.4 ms and blockade conductance of about 85-100 pA. During the translocation measurements, a long event of about 1.3 ms was found to have high blockade conductance of about 150 pA due to graphene-DNA interactions.
Chapter 4
Discussion

The novel part of this research is the fabrication procedure and DNA translocation through graphene nanogaps. This procedure for graphene nanogap fabrication does not involve transmission electron microscope (TEM), making it a cost-effective alternative to other proposed models. With the use of readily available equipment and chemicals, it is easy to fabricate a high yield of samples simultaneously, and at highly marketable production level.

An unstable current was observed during translocation measurements. This seems to appear in the devices without polymer on the graphene membrane. The unstable ion current may have been a result of the graphene’s position as a free standing membrane, requiring longer time differences between baseline currents during the translocation of DNA. The ion current seems relatively stable with the use of a stiffer polymer (PMMA) to restrain the graphene flake.

Table 4.1 shows the comparison of the results of graphene nanopores with the results of graphene nanogap from this research. For an applied voltage of 39 mV, we recorded an average conductance blockade, $\Delta G$ of 1.3 nS, which is similar to that for a graphene nanopore under the applied voltage of 200 mV observed by the group from TU Delft (6). The average translocation time is observed to be 2 ms which is independent of the membrane thickness. By increasing the applied voltage, there may be a possibility of increasing number of translocation events.
### Table 4.1: Comparison of DNA translocation through graphene nanopores results (6, 23, 24) with the results of DNA translocation through graphene nanogaps.

<table>
<thead>
<tr>
<th>School</th>
<th>Applied Voltage</th>
<th>KCl Concentration, C</th>
<th>Size</th>
<th>Conductance blockade, ΔG</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delft (6)</td>
<td>200 mV</td>
<td>1 M</td>
<td>48 kb</td>
<td>1.5 nS</td>
<td>200 ns/base</td>
</tr>
<tr>
<td>U Penn (23)</td>
<td>100 mV</td>
<td>1 M</td>
<td>NA</td>
<td>4.5 nS</td>
<td>5-30 ns/base</td>
</tr>
<tr>
<td>Harvard (24)</td>
<td>160 mV</td>
<td>3 M</td>
<td>10 kb</td>
<td>8.1 nS</td>
<td>20 ns/base</td>
</tr>
<tr>
<td>CSUN</td>
<td>39 mV</td>
<td>0.1 M</td>
<td>48 kb</td>
<td>1.3 nS</td>
<td>20 ns/base</td>
</tr>
</tbody>
</table>

Figure 4.1 (a) shows a plot of conductance blockade, ΔG versus KCl concentration, C, for the results shown in table 4.1. For DNA detection experiments, a large conductance change is desirable. If all the other variables are being held constant, the conductance can be varied by changing C. Therefore, a particular experiment can be made more favorable by simply increasing C. A more fair comparison between the different approaches is therefore to compare the results by taking into account the C that was used. The first order least-square fit is a guide to the eye that indicates the expected behavior ΔG ∝ C. As can be observed from their location above the line shown in figure 4.1 (a), the U Penn and CSUN experiments are intrinsically more sensitive.
Figure 4.1: Plots for the results showed in table 4.1; (a) Conductance blockade, $\Delta G$ versus KCl concentration, $C$, (b) Velocity, $v$ versus $V^2$.

For rapid sequencing of DNA molecules, a large translocation speed is desirable. If all the other variables are being held constant, the translocation speed can be varied by changing the applied trans-membrane voltage, $V$. Therefore, a particular experiment can
be made favorable by simply increasing $V^2$. A fair comparison between the different approaches is therefore to compare the results by taking into account the $V^2$ that was used. The first order least-square fit is a guide to the eye that indicates the expected behavior $v \alpha V^2$. As can be observed from their location above the line in figure 4.1 (b), the U Penn, CSUN and Harvard experiments show better translocation.

During the measurements, it was noticed that not all of the devices provided effective DNA translocation through suspended graphene membrane, some devices were either wide open, completely closed, or were immediately clogged upon adding DNA. In order to obtain high functional yield of gaps, membrane stability and wettability should be improved. Moreover, preventing DNA from sticking to the graphene makes the gaps clog less which may increase the number of events during the DNA translocation through the nanogap.
Chapter 5

Conclusion and Outlook

In summary, I have presented the first rapid translocation of DNA molecules through graphene nanogaps. Several devices were produced and their conductances observed through a graphene nanogap, as shown in figure 3.2. DNA translocation has been achieved through several graphene nanogaps, however, there were not enough data points to sufficiently test the conductance blockade model. Graphene nanogap devices were unstable and large ion current noise was observed which could be improved by using a stiffer polymer on the nanogap. Future work will focus on improving the reliability of the devices, single-strand DNA translocation and ultimately DNA sequencing through graphene nanogaps.
References

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