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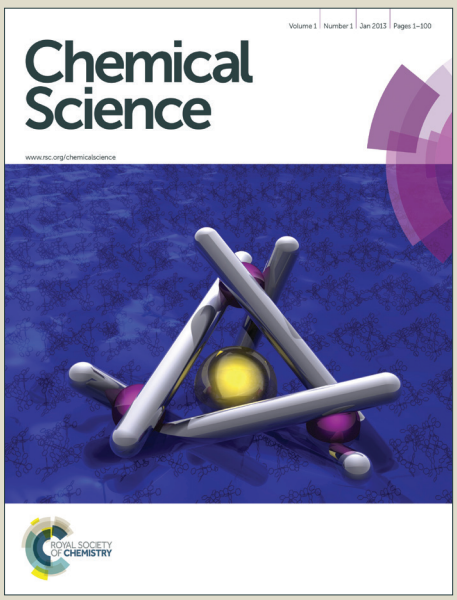

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Structure determined charge transport in single DNA molecule break junctions

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Kun Wang,[a] Joseph Hamill,[a] Bin Wang,[a] Cunlan Guo,[a] Sibo Jiang,[b] Zhen Huang[b] and Bingqian Xu*[a]

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Experimental study in charge transport properties associated with ionic environment change related structural variations will provide essential physical information in realizing the nature of DNA molecules. This work reports on the experimental study about the change of electronic transport properties induced by a conformational transition of a poly $d(GC)_4$ DNA. By gradually increasing $MgCl_2$ concentration from 0M to 4M in the buffer solution, the conductance of the single DNA molecule revealed a two orders of magnitude decrease. CD measurements confirmed a B to Z conformational transition caused reduction in conductance. With a stretch-hold mode SPMBJ technique, this B-Z transition process was monitored and a transition trend line was successfully achieved merely from conductance measurements. The transition midpoint occurred at $MgCl_2$ concentration of 0.93M for this DNA sequence. This method provides a general tool to study transitions of molecular properties associated with conductance differences.

Introduction

DNA, the repository of genetic information, has gained considerable attention because of its potential application in tomorrow's molecular electronics, such as building DNA chips.[1, 2] To pave steps towards this goal, great efforts have been made experimentally and theoretically.[3, 4] In order to approximate natural conditions, experiments are usually performed in appropriate buffer. However, discrepancies exist not only between experimental results and simulated data but also among different experimental attempts on similar DNA molecules. For example, a wide range of electronic properties for λ-DNA, varying from insulating, conducting to even superconducting, were reported by different groups.[5-8] Similarly, for the same DNA, the conductance measured in solution was an order of magnitude greater than the conductance in dry condition.[7] As various simulations suggested, it is quite possible that these discrepancies are caused by different experimental conditions, especially different ionic environments in buffer solutions where DNA electronic properties were measured.[9-11] Ions surrounding DNA molecules could not only vary the degree of charge delocalization, but also perturb the structure of DNA molecules.

DNA molecules have proven to exhibit surprising conformational versatility, while retaining remarkable precision and uniformity.[12] Not just right handed (RH) B- and A-DNA, left-handed (LH) Z-DNA has also been explored by chemists and biologists due to its biological and medical significance.[13-15] Using circular dichroism (CD), the ionic conditions necessary to induce a conformation-shift from a right-handed (RH) B-DNA to a left-handed (LH) Z-DNA helix was determined for various counterions.[16-18] The presence of ethanol in addition to alkane metal ions in solution was also reported to cause a RH internal switch from B- to A-DNA.[19, 20]

The conductance of short strands of RH double helix DNA has been determined theoretically and experimentally.[4, 21] Concurrent simulations highlighted the conductance changes due to conformational perturbations.[22, 23] The dependency of these conformational perturbations on salt concentration suggests that counterion configurations around DNA played a prominent role in charge migration especially in solutions with high salt concentration.[3, 9, 10, 24, 25,26] Therefore, the ionic circumstance around DNA is of paramount influence on electrical measurements but this information is unfortunately still missing to date. Systematic investigations into the correlations between the ionic circumstance in buffer solution and the subsequent DNA physical conformational alteration induced conductance changes will provide fresh understanding of the nature of DNA, as well as provide essential groundwork for the development of DNA-based molecular devices.

Given that previous DNA conductance measurements were performed in buffer solutions containing invariable ionic concentration, it is still ambiguous how electronic properties of a short DNA molecule vary as ionic environment changes and what the underlying mechanism could be. Herein, we report on conductance measurements of poly d(GC)$_4$ DNA based on SPM break junction (SPMBJ) technique (**Fig. 1**). By gradually increasing $MgCl_2$ concentration in the buffer solution, a two orders of magnitude decrease in conductance was revealed. Circular dichroism (CD) measurement proved it to be the secondary molecular structural transition induced reduction in charge transport ability of short strand DNA. Combined with CD, we further developed a novel method to determine the transition degree (TD) simultaneously beside conductance measurements.

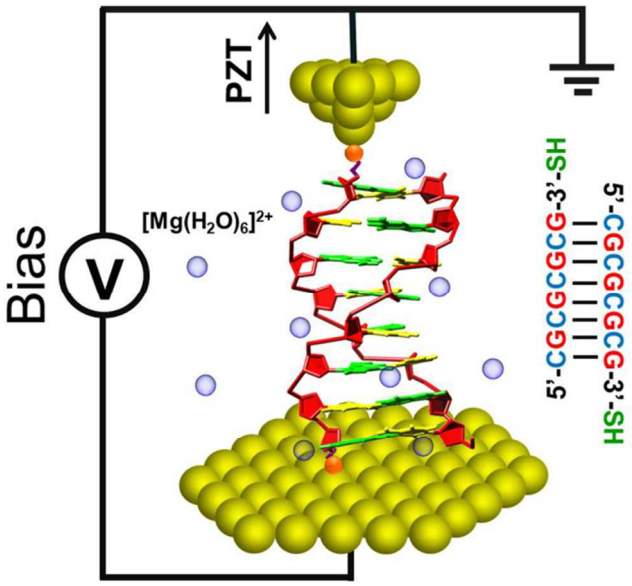

Fig. 1 Experimental schematic of SPM break junction. $[Mg(H_2O)_6]^{2+}$ ions are represented by spheres around DNA skeleton. The three hydrogen bonds connecting cytosine and guanine are not shown in DNA structure.

Results and Discussion

Under a constant bias voltage of 0.3V, the static conductance of poly d(GC)$_4$ DNA was measured in buffer solutions with gradual increase of $MgCl_2$ concentration (0M, 0.1M , 0.5M, 1M, 1.5M, 2M, 3M and 4M). The 3' end of single strand DNA was modified with a thiol group in order to bond with the Au electrodes to form the molecular junctions. The DNA sample solution prepared at each $MgCl_2$ concentration was dropped on freshly flamed Au (111) to form DNA monolayer after 40min incubation. Molecular junctions were formed when STM tip approached the Au surface and then broke when STM tip retracted away from the surface. During each of the tip retracting process, a conductance trace was recorded. By repeating this, around 1000 conductance traces were collected for the construction of the final conductance histogram at each $MgCl_2$ concentration. All the measurements were conducted at room temperature (~23˚C). More experimental details are provided in **S1 (see ESI†)**. A continuous-stretch mode (CSM) SPMBJ was performed for transient Au-DNA-Au junctions by retracting the tip continuously,[27] and a stretch-hold mode (SHM) SPMBJ was applied to create stable junctions by modifying the tip retraction process with a periodic pause.[28]

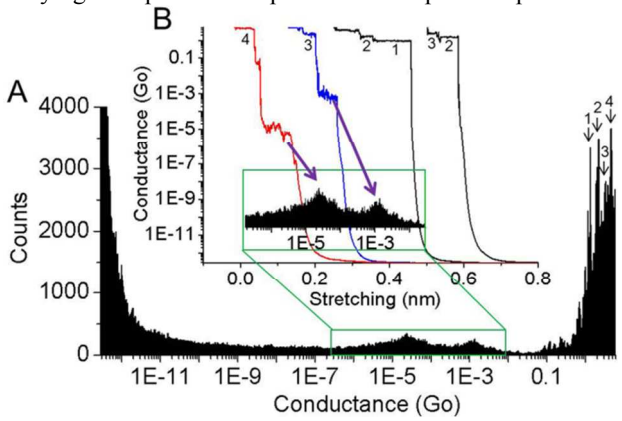

Fig. 2 Log-scale conductance measurement was performed in 1M $MgCl_2$ solution using CSM-SPMBJ. (A) Log scale conductance histogram was constructed from around 1000 log-scale traces under CSM. (B) Typical conductance traces were shown. The left two traces exhibited plateaus corresponding to peaks at around $1\times10^{-5}G_0$ and $1\times10^{-3}G_0$, respectively. Numbers labelled in conductance histograms and traces represent integer multiples of conductance quantum G_0. The inset in B shows the zoom in of squared area in log-scale conductance histogram.

A logarithmic-scale STM scanner was first applied under CSM to monitor a broad range for a first glance at the possible conductance sets of poly d(GC)$_4$ DNA in 1M $MgCl_2$ buffer solution which is supposed to simultaneously access various DNA conformations. In addition to the sharp peaks at integer multiples of conductance quantum G_0 that correspond to the gold quantum contacts, the histogram also exhibited two apparent peaks at lower conductance range: around $1\times10^{-5}G_0$ and $1\times10^{-3}G_0$, respectively (**Fig. 2**). Representative log-scale conductance traces are shown in **Fig. 2b**. Previous measurements on the same DNA sequence confirmed the peak at 1×10^{-3} G_0 to be the conductance at a standard double helix B-conformation.[21] Log-scale data offered a complete scope of possible locations of conductance peaks, but failed to provide highest resolution of details which is necessary for electrical measurements at single-molecule level. In order to accurately determine the conductance value and gain more details of the DNA molecular junction, linear scale STM scanner was then used for a series of different $MgCl_2$ concentrations under both CSM- and SHM-SPMBJ. To measure the conductance of ~$1\times10^{-3}G_0$, we chose the measurement window in the higher conductance region (**Fig. 3a**). As is shown in **Fig. 3a**, a representative conductance trace (the rightmost) contains a very low plateau at the same level of baseline offset shift. Unfortunately, this information was entirely washed out by slight shifting of the conductance trace baseline under this window. To reveal the lower conductance plateau, we measured

the conductance curves by focusing on the lower conductance region, which show a conductance of ~$3\times10^{-5}G_0$ (**Fig. 3b**). Therefore, using SHM-SPMBJ measurements, two peaks were accurately measured to be $1.06(\pm0.27)\times10^{-3}G_0$ and $2.79(\pm0.64)\times10^{-5}G_0$ in 1M $MgCl_2$ solution, respectively. We then measured the conductance of the poly $d(GC)_4$ DNA under different $MgCl_2$ concentrations. For lower concentrations (0M, 0.1M, 0.5M), a conductance peak around $1\times10^{-3}G_0$ was determined, suggesting the DNA to be B-DNA. However for medium and high concentrations (1M~4M), a larger number of individual conductance traces appeared to have significant information at a much lower conductance value which was associated with the peak at around $1\times10^{-5}G_0$ under log scale. Control experiments conducted in pure 4M $MgCl_2$ solution with no DNA molecule implies that these peaks were dominantly contributed by DNA molecules rather than other factors like courterions and water molecules in the solution (**Figure S2a, see ESI†**). A two-dimensional correlation histogram (2DCH) was also demonstrated for the two measurement regions (**S3, see ESI†**). Strong anti-correlation regions (circled area) suggest the possibility that each conductance trace contained only a single conductance plateau, either at the height of one, or at two Au-DNA-Au junctions, but rarely both together.

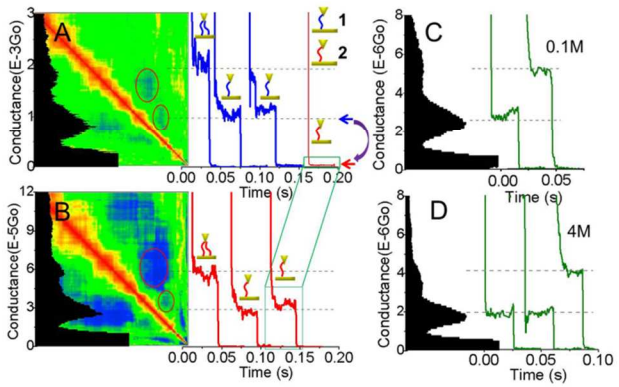

Fig. 3 (A) and (B) show the conductance measurement results of poly $d(GC)_4$ DNA. In 1M $MgCl_2$ solution, two sets of conductance values ($1\times10^{-3}G_0$ in A and $1\times10^{-5}G_0$ in B) were determined by conductance histograms using the measured conductance traces. In A and B, the rough schematics (1 and 2) of DNA molecular junctions are shown above the each conductance plateau. Short curved strand in blue and red represent the DNA molecules with high and low conductance, respectively. The number of short curved strand in each schematic represents how many DNA molecules were measured when the plateau was recorded. 2DCH show strong anti-correlation regions (circled in 2DCH). For 5'-CGCGAAACGCG-3'DNA, SHM conductance histograms, typical conductance traces measured at 0.1M and 4M are shown in panel C and D, respectively.

While the $1\times10^{-3}G_0$ conductance value was reported to be associated with B-DNA, the appearance of the conductance peak at the level of $1\times10^{-5}G_0$ could be attributed to several possible causes. Firstly, both base pair (bp) mismatch and the single strand DNA could be its source. As poly $d(GC)_4$ is the chosen sequence, there would be multiple mismatched bps once the bp mismatch took place. However, even the mismatch of a single bp leads to one order of magnitude decrease in conductance so that multiple mismatches will make the DNA nearly insulating,[29] which suggests the impossibility in observation of the conductance of the mismatched DNA molecules. Also, in our case, single strand DNA hardly existed due to the high melting temperature (>50°C) of DNA molecules in 1M $MgCl_2$ solution. Even if it existed, the single strand DNA could not form the molecular junction since only one end of the single strand was modified with a thiol group. Thus, the peak at the level of $1\times10^{-5}G_0$ is not resulted from single strand DNA or bp mismatch. Secondly, as many studies reported, variations in Au-S geometries, effective contact coupling and DNA solvation shell could also cause the decrease in conductance by orders.[30-33] To find out if these factors caused the conductance drop, another series of control experiments were conducted on the DNA sequence of 5'-CGCGAAACGCG-3' which has little perturbation in structure due to the three consecutive adenine bases sandwiched at the center of the sequence.[34, 35] In **Fig. 4c**, CD results suggested that this DNA still remained in RH B-conformation even after addition of high concentrations of $MgCl_2$. Under SHM, conductance of this DNA sequence was measured in $MgCl_2$ solutions prepared the same way as for poly $d(GC)_4$ DNA. As shown in **Fig. 3c and 3d**, the conductance only showed a negligible variation from around $2.5\times10^{-6}G_0$ in 0.1M $MgCl_2$ solution to $2.0\times10^{-6}G_0$ in 4M $MgCl_2$ solution. This small change is possibly caused by a slight structural perturbation of DNA in solutions with high $MgCl_2$ concentration confirmed by the CD measurements (**Fig. 4c**). No significant number of conductance traces containing low but meaningful plateaus like the case for poly $d(GC)_4$ DNA was observed with $MgCl_2$ concentrations spanning from 0M to 4M in the control measurements. Overall, both conductance measurements and CD results suggest that the influences of contact geometries, effective coupling and solvation shell were trivial in this study. Finally, the newly revealed peak, two orders of magnitude smaller in conductance, could be contributed by another conformation of poly $d(GC)_4$ DNA duplex.

Over a series of measurements, it was determined that the histogram peak at $1.06(\pm0.27)\times10^{-3}G_0$ did not have obvious change with small increases of Mg^{2+} concentration from 0M, 0.1M and 0.5M, even over the entire range of concentrations from 0M to 4M. Instead, the magnitude of this peak decreased with increasing Mg^{2+} concentration, while the magnitude of the other peak at $2.79(\pm0.64)\times10^{-5}G_0$ became more pronounced. This implies a clear ratio switch between these two peaks as Mg^{2+} concentration increases. The change in magnitude of two orders suggests not a linear relationship between DNA conductance and counterion concentration, but a significant regime change such as a compete change in DNA conformation.

A likely explanation is a change from RH B-DNA to LH Z-DNA, which can be tested by CD measurements since CD studies[16, 36] have thoroughly explored the ion-dependent

transition between B- and Z-DNA. Therefore, we conducted CD measurements on DNA samples under the same $MgCl_2$

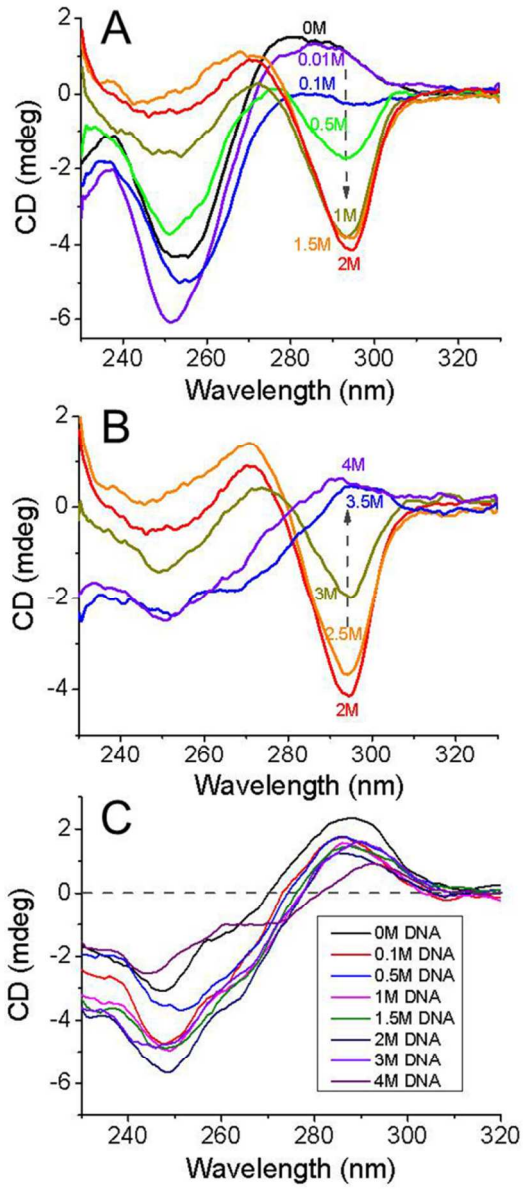

Fig. 4 (A) and (B) show the CD spectra of poly $d(GC)_4$ DNA measured in 0M~2M and 2M ~4M $MgCl_2$ solutions, respectively. The arrow in either panel shows the variation trend of CD intensity at 295nm as $MgCl_2$ concentration increases. Panel C illustrates the CD spectra of 5'-CGCGAAACGCG-3'DNA measured in 0~4M $MgCl_2$ solutions.

concentrations as the conductance measurements, and also two additional concentrations of 0.01M and 3.5M. In **Fig. 4a**, from 0M to 2M, it showed clearly that we had a complete transition from B-DNA spectra (a positive peak at 275 nm and a negative peak at 250nm) to Z-DNA spectra (a negative peak at 295nm and a positive peak at 265nm) similar to other reports.[16, 36, 37] An unexpected inconsistency in CD trend was observed in concentrations beyond 2M (**Fig. 4b**). Negative peaks with increasingly lower intensity were observed at 295 nm until the peaks eventually became a small bump at very high $MgCl_2$ concentrations (3.5 M and 4 M). We suggest that aggregation of individual DNA molecules was the cause of this odd trend at very high $MgCl_2$ concentrations (3.5M, 4M) because high Mg^{2+} concentrations can readily induce aggregation of short DNA molecules and the spectra at 3.5M and 4M resembles curves associated with ψ-form DNA condensations.[38-41]

To confirm, STM imaging was carried out on samples prepared the same way as for CD measurements (**Fig. 5**). At 0.1M, a well-assembled monolayer of DNA molecules was observed. After drying the solution with high purity nitrogen, imaging in air showed a negligible aggregation spot only in one of a few images which may be due to the high concentration (5μM) of DNA molecules. In 4M $MgCl_2$ solution, imaging in solution showed lots of aggregation spots in all images. The imaging in air showed even more aggregation spots because drying the sample forced floating aggregation bundles which could not be seen in solution to attach on the surface. More STM images are provided in **Fig. S1 (see ESI†)**. A control experiment conducted in pure 4M $MgCl_2$ solution with no DNA molecule revealed no aggregation spot via both imaging in solution and in air, which excludes the possibility that these spots were induced by condensation of salt (**Fig. S2b and S2c, see ESI†**).

It has to be noted that the buffer pH decreased as the $MgCl_2$ concentration increased (Table S3). Previous CD studies using the same DNA sequence proved that low pH (<3.6) could also contribute to the B-Z conformational transition.[42, 43] Therefore, other than high ionic concentration, the low pH of the buffer solution is another factor inducing the B-Z transition when $MgCl_2$ concentration increased high (>3M). The exact concentration of $MgCl_2$ dissolved in buffer solution decreased since the buffer pH reduced. Given that it is hard to know the exact concentration, we will keep using the concentration we labelled when we prepared the solution in the following discussion.

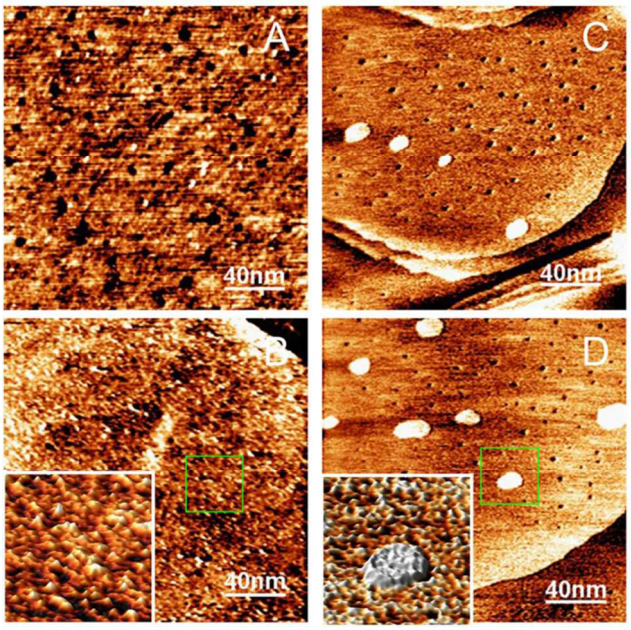

Fig. 5 STM imaging for DNA samples in 0.1M (A, C) and 4M (B, D). Panel A and B are images scanned in solution under 0.1M and 4M, respectively. Panel C and D show the images obtained in air under 0.1M and 4M, respectively.

DNA aggregation made CD fail to distinguish Z-DNA at high $MgCl_2$ concentrations; however the conductance measurement has little difficulty handling aggregation because STM can image prior to conductance measurements. Before measuring, smooth locations indicative of DNA monolayer on the Au surface were chosen to conduct measurements. The Au surface itself contributed in breaking up aggregations, and any aggregation floating in solution would not have influenced conductance measurements, and certainly would not have contributed to histogram peaks.

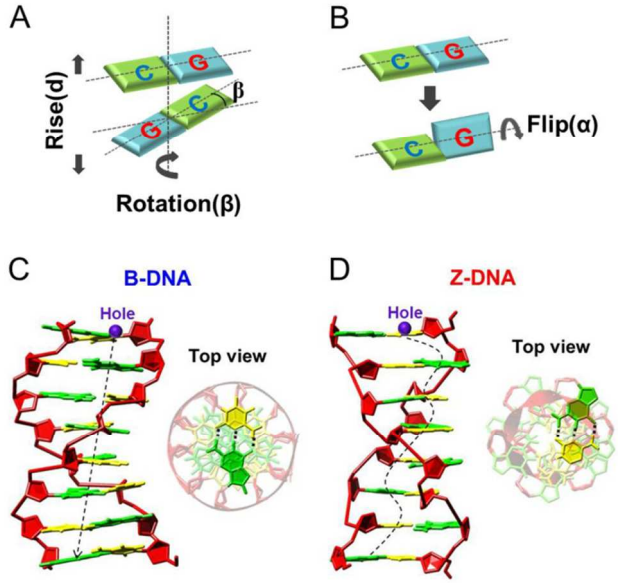

Fig. 6 (A) Schematics of relative change between neighboring bps during the B-Z transition; (B) The schematic for guanine flipping. (C) and (D) show the structural side view and top view of B- and Z-DNA, respectively. In (C) and (D), the dashed lines demonstrates the intra-strand path for hole migration.

The cause of conductance decrease from B- to Z-DNA

The cause of the decrease in DNA conductance during B-Z conformational transition may come from a few sources but is primarily due to the structural change induced breaking of π-π orbital stacking between neighboring bps. In **Fig. 6a**, the average rise (d) between adjacent bps was increased 14% from 0.332nm (in B-DNA) to 0.380nm (in Z-DNA), which could rapidly reduce the charge transfer rate; the axial twist (β) in Z-DNA was determined to be -30° which far deflects from the angle 36° for highest charge transport in B-DNA. Most importantly, the transition result in a flipping of guanine (G) bases by almost 180° for this DNA sequence (**Fig. 6b**).[23] The alternating of *anti* and *syn* orientations transforms the location of G bases from the center of the helix in B-DNA to the edge of the helix in Z-DNA. These changes cause the bases to be held on the edge of the helix and place guanine bases over the neighboring cytosine's sugar residues. The result is a disruption of the ordered π-π stacking which is the major source of the relatively high conductance of B-DNA (**Fig. 6c and 6d**).[3, 44]. Although the diameter of Z-DNA is narrower, charge transports much easier along neighboring bps longitudinally rather than laterally, and the broken stacking, increased rise and spiral intra-strand path result in a significant reduction in conductance from B- to Z-DNA.[45] Since the HOMO is dominated by G orbitals in sequences such as this,[4] the flipping of G will have a detrimental effect on distribution of effective orbitals for charge transport. According to the possible backbone conduction model[46], the contorted "zigzag" backbone in Z-DNA is less favored than the standard double helix in B-DNA, thereby lowering the conductance.

Apart from the impact of DNA intrinsic structural change, the surrounding counterions and water molecules also affect the charge transport process. It was reported Mg^{2+} could bind to G and phosphate through its hydration shell.[47] The estimation based on our case shows that there is on average 0.8 Mg^{2+} ion around a single DNA junction in 0.1M $MgCl_2$ solution. But on average 8.0 Mg^{2+} ions are available to bind to a single DNA molecule at 1M and even more ions are possible as the concentration increases (see S5). It has to be noted that the dynamic movement of Mg^{2+} ions in solution greatly lowers the binding opportunity between ions and DNA. Thus, it is plausible that higher concentrations (3M, 4M) are necessary to stabilize most DNA molecules in Z-form.

Simulations[9] suggested the delocalization of electron states induced by hydrated ions around DNA. Extra pathways for charge hopping could occur via ionization of phosphates and the doping of DNA grooves by Mg^{2+}, water states and bases states.[48, 49] Compared with the breaking of π-π orbital stacking, influences from water and counterions are presumed to be minor effect.

Transition Degree (TD)

To quantify this DNA conformational change, we calculated the transition degree (TD) defined as the percentage of B-DNA which converts to Z-DNA as determined by our SHM conductance measurements. As an analogue to CD reported by others,[16] the key feature of our conductance histograms which allows the distinction between B- and Z-DNA is the two separate peaks. SHM SPMBJ technique predicts that each plateau in every conductance trace is ideally equal in counts due to the constant duration, though the position changes. Therefore, each SHM conductance trace equally contributed to the final conductance histogram. Thus, the histogram is composed of a finite number of equally sized plateaus, the position of which is concentration dependent. By separately constructing histograms from two sets of traces, the transition degree was determined by SHM-TD = $A_Z/(A_Z + A_B)$, where A is the sum of counts beneath the first peak area in SHM histograms. More calculation details can be found in **S6 (see ESI†)**.

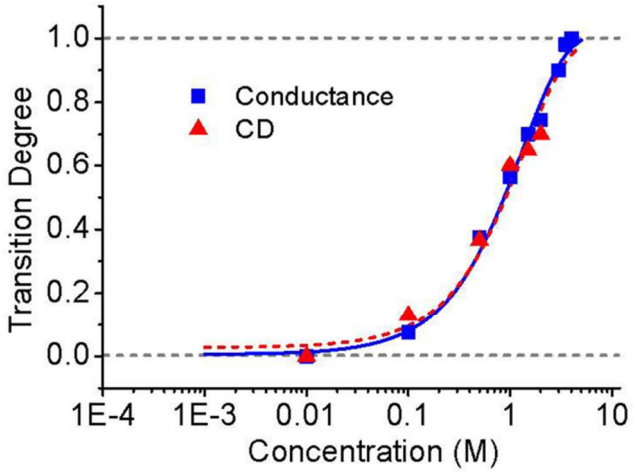

Fig. 7 TD vs log $MgCl_2$ concentration. SHM-TD data points (■) and its corresponding Boltzmann fitting (solid curve). CD-TD data points (▲) and its fitting (dashed curve).

To accurately mark the transition midpoint where 50% of B-DNA was converted to Z-DNA, it was important to first note that at low concentrations (0.1M) where past research agreed the conformation is predominantly B-DNA. The Boltzmann fitting on SHM-TD data (squares in **Fig. 7**) suggested the transition midpoint to be 0.93M. This was larger than the previously reported value around 0.66M for indeterminately long strands of poly $d(GC)_m$ in $MgCl_2$ solution using CD.[16] But it well matched the trend reported in the same paper that the shorter the DNA length, the larger the necessary concentration to induce a 50% transition. Due to the sensitivity our electrical measurement has to high ionic concentration, we were unable to obtain meaningful results beyond 4M. Just the same, the Boltzmann fitting suggests that the B-Z transition was saturated at around 4M. Using the well-behaved part (0M~2M) of CD results (triangles), we also plotted a CD-TD trend line (dashed curve). Boltzmann fitting still worked for estimating an entire transition line based on these CD results (**Table S2, see ESI†**). It suggested a transition midpoint (0.91M) very close to the SHM-TD result. SHM- and CD-TD trend lines overlaps reasonably well.

Conclusions

Based on the SPMBJ technique, by increasing the concentration of $MgCl_2$ in buffer solution, two different DNA conformations (B and Z) were distinguished exclusively by their difference in conductance due to physical and electronic differences between the two conformations. Experimental results revealed that the increase of ionic concentration in DNA sample solution induced a secondary structure transition of DNA molecules and the conformational change reduced DNA conductance by two orders of magnitude. Our technique successfully monitored changes in DNA conformation at a spatial and temporal resolution never before achieved, providing a powerful tool to explore some of the more confounding problems in molecular biology. In addition, using a SHM modification, our method offers an alternative way for building up transition trend lines between two DNA conformations, particularly when CD fails to work. This method is a general tool to study transitions of other molecular properties associated with conductance differences.

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Notes and references

[a] *Single Molecule Study laboratory, College of Engineering and Nanoscale Science and Engineering Center, University of Georgia, Athens, GA 30602, USA. Email: bxu@engr.uga.edu*

[b] *Department of Chemistry, Georgia State University, Atlanta, GA 30303, USA.*

† Electronic Supplementary Information (ESI) available: Electrical measurement details about log-scale and linear-scale setup, details about DNA structure simulation and 2DCH, results of control experiment conducted in pure 4M $MgCl_2$ solution with no DNA molecule, estimation on numbers of Mg^{2+} ion around DNA in buffer solution and TD, and pH values and specific TD results at each concentration. See DOI: 10.1039/b000000x/

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TOC

Single DNA conductance measurements with increasing $MgCl_2$ concentrations unambiguously revealed two DNA (B and Z) conformations and the B-Z transition process.