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# The effect of oxidative damage on charge and spin transport in DNA

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## Supporting Information Placeholder

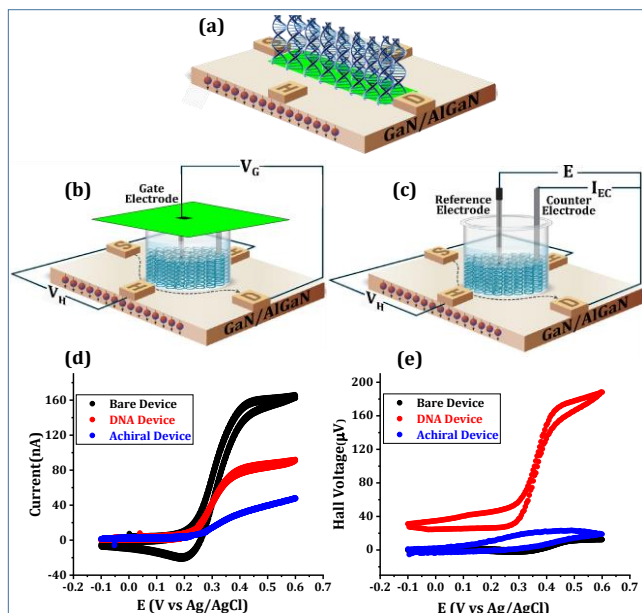
**ABSTRACT:** A Hall device was used for measuring spin polarization on electrons that are either reorganized within the molecules or transmitted through the self-assembled monolayers of DNA adsorbed on the device surface. We were able to observe spin-dependent charge polarization and charge transport through double-stranded DNA of various lengths and through double-stranded DNA containing oxidative damage. We found enhancement in the spin-dependent transport through oxidatively damaged DNA. This phenomenon can be rationalized either by assuming that the damaged DNA is characterized by a higher barrier for conduction or by charge transfer through the DNA being conducted through at least two channels, one involves the bases and is highly conductive but less spin selective, while the other pathway is mainly through the ribophosphate backbone and it is the minor one in terms of charge transmission efficiency, but it is highly spin selective.

Electron transport through DNA is a vivid topic of research powered by two goals. One relates to the application of DNA in molecular machinery<sup>1,2</sup> and molecular electronics,<sup>3-6</sup> and the second relates to the possible role of electron transport through DNA in the damage control system in the cell.<sup>7</sup> The present work relates to both subjects. 8-Oxo-7,8-dihydro-2'-deoxyguanosine (8-oxoG) is among the most common forms of oxidative DNA damage found in human cells. It is known that there exists a network of pathways that protect cells from the deleterious effects of this damage.<sup>8-10</sup> 8-OxoG is minimally perturbing to duplex DNA; both 8-oxoG:C and 8-oxoG:A base pairs have only minor effects on double-stranded DNA structure and stability.<sup>11,12</sup> This makes it particularly challenging for repair enzymes to locate. Hence the question of damage recognition by the repair machinery is a long standing one. It has been suggested that the mechanism of efficiently locating damage within the entire genome might be related to modulations in the electronic properties of the DNA.<sup>7,13,14</sup> Recently it has been shown that there is a dependence of the efficiency of the electron spin-selective transport on the DNA helical structure.<sup>15</sup> This work is consistent with other studies that demonstrated that DNA is an efficient spin filter.<sup>16-18</sup>

Here a device was utilized that allows to measure directly the spin-dependent polarizability of molecules as well as the spin and charge

transport across the molecules, applying spin-dependent electrochemistry (See Fig. 1).<sup>19</sup> The system is based on a Hall device patterned on a GaN/AlGaN two-dimensional electron gas (2DEG) structure. A current of 10 $\mu$ A is derived between the source and drain electrodes. Unlike former studies, where the molecules were adsorbed on top of the GaN substrate, here the Hall device is coated with a thin gold film.<sup>20</sup> The gold film serves two purposes: it enables binding of thiolated molecules to the substrate, through the well-established thiol-gold process, and it stabilizes the potential on the surface and therefore increases the stability of the measurements. The setup can operate in two modes. In the first, it is used to measure the charge polarization-induced spin polarization of chiral adsorbed molecules. By applying an electric field between the gate electrode and the device, the self-assembled monolayer is charge polarized. If this charge polarization is accompanied by spin polarization, a Hall voltage is measured in the device (Fig. 1b).<sup>21</sup> In the second, spin-dependent electrochemical (SDE) measurements are carried out using standard three electrodes electrochemical cell.<sup>20</sup> Here, the Hall device serves as the working electrode in the electrochemical cell. While measuring the CV curve, the Hall potential is monitored simultaneously, so as to obtain information on the spin selectivity of the process (Fig. 1c).

For establishing the ability of the experimental setup to monitor SDE, Fig. 1d shows cyclic voltammetry (CV) curves obtained for a bare device, a device coated with a monolayer of double-stranded (ds) DNA, and a device coated with a monolayer of achiral molecules, i.e. 1-hexadecanethiol (HDT). As expected, the current obtained with the bare device is the highest. However, despite the thickness of the achiral monolayer is smaller than the monolayer of ds-DNA, the current through DNA is higher, an effect already observed in the literature and ascribed to efficient electron transfer through chiral systems.<sup>22,23</sup> Fig. 1e shows the Hall potential, recorded simultaneously with the CV experiment. Only in the case of a device coated with DNA, a significant potential curve is measured, as expected based on the chiral induced spin selectivity (CISS) effect.<sup>8</sup>



**Figure 1:** (a) Scheme for a DNA monolayer on the Hall device (b) Hall setup for conducting spin polarization studies, when a Hall device is coated with a monolayer of chiral molecules and is covered with electrolyte. On the top, a gate electrode (in green) is used to apply an electric field. The electrode is insulated from the solution and therefore no faradaic current flows between the gate and the Hall device. (c) A spin-dependent electrochemistry setup in which the Hall device coated with the chiral monolayer is used as the working electrode in the electrochemical cell. (d) The CV plots obtained with the bare device (black) coated with a 30-bp long DNA monolayer (red) and a device coated with a monolayer of achiral molecules, 1-hexadecanethiol (HDT). (e) The Hall potential measured simultaneously with the CV curves in (d).

In the first part of the study, we demonstrate the ability of the setup by measuring the spin polarization and spin and charge transfer using electrochemistry, when the Hall device is coated with self-assembled monolayers of double stranded DNA of three different lengths, 20, 30 and 40 base paired (bp) (sequences given in SI). The aim is to verify that the results obtained with the current electrochemical setup are consistent with former spin-dependent studies performed on DNA.

In the second part, spin polarization and spin electron transfer information are obtained by measuring monolayers of three different double-stranded DNA that are:

#### 40nt dsDNA without any damage: All-G

(1) 5'-TAT ATG TTA TTC TTA TTG TTA TTC TTT ATG  
TTT TTT TTT T-(CH<sub>2</sub>)<sub>3</sub>-S-S-(CH<sub>2</sub>)<sub>3</sub>-OH

(2) 5'-AAA AAA AAA ACA TAA AGA ATA ACA ATA  
AGA ATA ACA TAT A

#### 40nt dsDNA with one damage site: 1-OG

(1) 5'-TAT ATG TTA TTC TTA TTG TTA TTC TTT AT8  
TTT TTT TTT T-(CH<sub>2</sub>)<sub>3</sub>-S-S-(CH<sub>2</sub>)<sub>3</sub>-OH

(2) 5'-AAA AAA AAA ACA TAA AGA ATA ACA ATA  
AGA ATA ACA TAT A

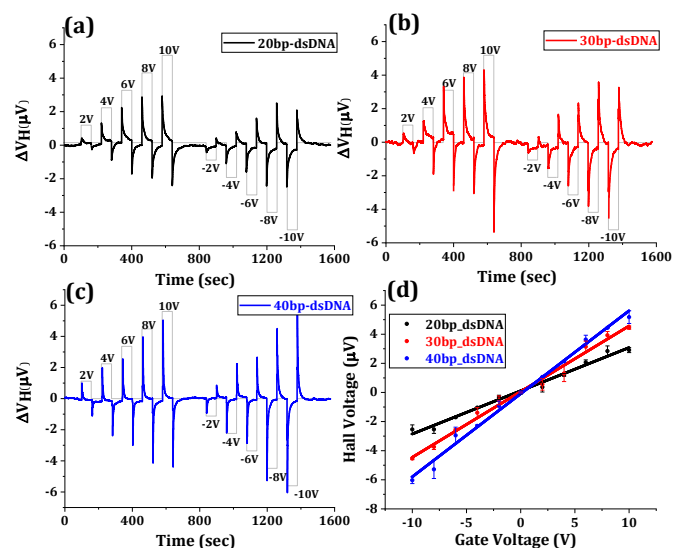
#### 40nt dsDNA with three damage sites: 3-OG

(1) 5'-TAT AT8 TTA TTC TTA TT8 TTA TTC TTT AT8  
TTT TTT TTT T-(CH<sub>2</sub>)<sub>3</sub>-S-S-(CH<sub>2</sub>)<sub>3</sub>-OH

(2) 5'-AAA AAA AAA ACA TAA AGA ATA ACA ATA  
AGA ATA ACA TAT A

Where 8 = 8-oxo-dG

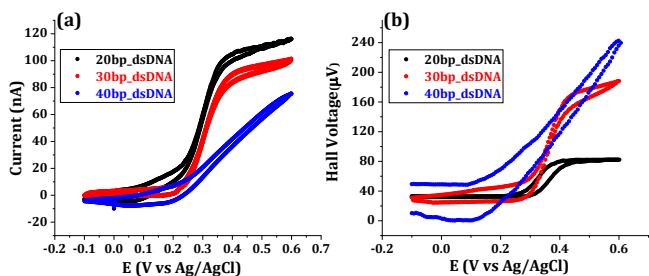
The goal here is to probe the effect of oxidative damage on electron transfer and spin transfer efficiency.



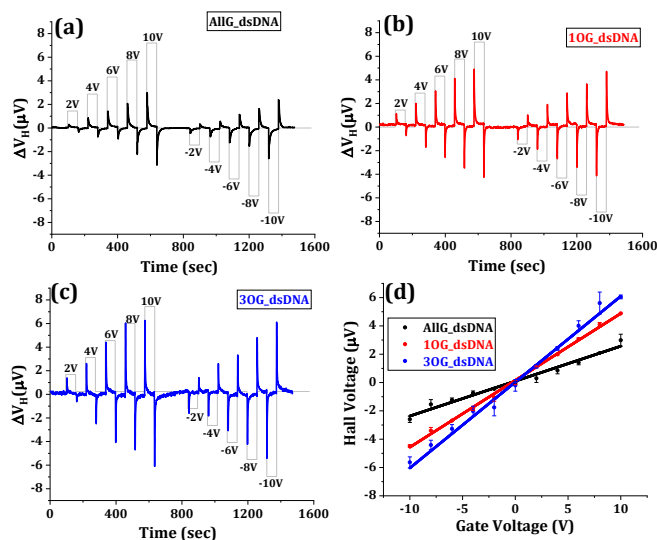
**Figure 2:** Polarization experiments performed on Hall devices coated with ds-DNA of different lengths. The Hall potential is shown as a function of the gate voltage. Chrono Hall potentials were recorded on (a) 20bp (b) 30bp and (c) 40bp long DNA with sequential gate pulses from -10V to 10V in the step of 2V. (d) The Hall potential as a function of the gate voltage is shown for the three devices.

Figure 2 presents the results obtained when polarization experiments were conducted on three lengths of ds-DNA. When a potential difference is applied between the gate electrode and the Hall device, a fast rising peak is observed that decays at longer time scale (also depend on the applied pulse width which is around 60 sec). The decay is attributed to the formation of a double layer in the electrolyte solution that screens the potential. In Figure 2d the peak of the Hall voltage is plotted as a function of the gate voltage for the three DNA monolayers. The Hall signal depends linearly on the voltage applied, as expected in the case of charge polarization, and the slopes are 2:1.5:1 for the 40, 30 and 20 base pair duplexes, which is proportional to the length of the molecules. This result is consistent with former studies which showed an approximately linear dependence of the spin selectivity on the length of double-stranded DNA.<sup>16,17</sup>

Fig 3 shows the results from the SDE study. Ferrocene was used as the bulk redox couple. While the current in the CV experiments drops with increasing length of the DNA, the Hall potential increases in the ratio 1;2.3;2.95 for the 20, 30 and 40 bp ds DNA, respectively, when the ratio is associated to the Hall signal measured at a potential of 0.6 V. Here it seems that the spin polarization increases super-linearly with the length, probably due to the lower potential applied, which makes the spin selectivity more prominent.



**Figure 3:** The results from SDE experiments performed with the Hall device as working electrode; Pt wire and Ag/AgCl were the counter and reference electrodes respectively. The experiment was performed in 0.1M PBS buffer as electrolyte with ferrocene as the redox couple. (a) CV curves recorded for the 20 bp (black), 30 bp (red) and 40 bp (blue) long DNA monolayers. (b) The Hall potential was measured simultaneously with the CV plots.

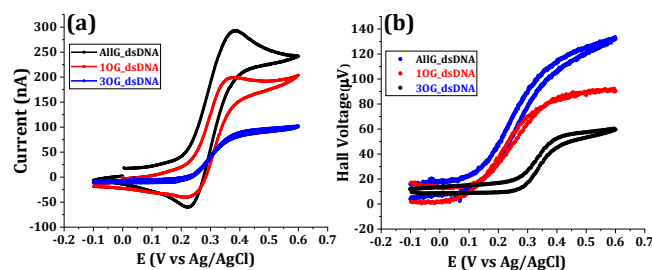


**Figure 4:** Polarization experiments performed on Hall devices coated with monolayers of double-stranded DNA having either no damage (black), one (1OG-red) or 3 (3OG-blue) oxidized guanines. The Hall signal is presented for various gate voltages. Chrono Hall potentials were recorded on (a) All G (no damage) (b) 1OG and (c) 3OG DNA with varying gate potentials from -10V to 10V with a step size of 2V. (d) The dependence of the Hall potential on the applied gate voltage.

In the second part of the study, we investigated the effect of oxidative damage on the charge and spin transport through double-stranded monolayers of DNA. Figure 4 shows the effect of the damage on the spin polarization. Surprisingly the damage increases the spin polarization quite dramatically. The dependence of the spin polarization on the applied voltage is linear in all cases, but the slope increases upon having a single OG base, while adding two additional OGs increases only mildly the slope. It is important to realize that this study is not probing actual charge/spin transport, but charge/spin polarization.

Figure 5 presents the results from the SDE experiments performed with the same monolayers composed of double strands having damages in the base pair sequences. While the current in the CVs decays dramatically due to the damage in the base pairs of the DNA, the spin polarization increases, so that at 0.6 V it has the ratio of 1:2:3 for the undamaged, 1OG and 3OG

respectively. This result is consistent with the spin-dependent polarization data shown in Fig. 4d. In experiments performed with the single stranded DNA, All-G, 1-OG, and 3OG, the ratio in the spin-polarization signals is similar as for the double stranded, however the current signal is not stable and decays after a short time, see SI Fig. S9.



**Figure 5:** The results from SDE experiments performed on monolayers of double-stranded DNA with the Hall device as working electrode, Pt wire and Ag/AgCl were the counter and reference electrodes, respectively. (a) CV curves recorded for undamaged strand (black), strand with 1OG damage (red) and strand with 3OG sites (blue). (b) The Hall potential measured simultaneously with the CV measurements.

The damage-induced spin polarization obtained here, together with the dramatic reduction in the charge transport, may result from two different reasons. The damage can cause an increase in the activation energy barrier for the conduction, thereby increasing the spin selectivity effect.<sup>23</sup> Another possibility is that charge transport through a double-stranded DNA occurs through at least two pathways. For example, it is possible that the prominent conduction path involves the bases, while a second path is through the backbone. The damage in the bases blocks the conduction through the first channel, at least partially, and then most of the charge transport occurs through the backbone, which is more spin selective due to its chirality. The decrease in the current upon introduction of oxidative damage in the DNA (Fig. 5a) and the stronger dependence of the spin polarization on the applied voltage (Fig. 5b) may then indicate a higher barrier for charge transport in the case of the damaged DNA, but with a more efficient spin selectivity.

The experimental results here reported are consistent with both proposed mechanisms. It is interesting to realize that in previous studies, where the interaction of monolayers of damaged DNA with low energy photoelectrons was investigated, a clear-cut indication for the conduction occurring via the backbone was observed.<sup>13</sup> This conduction explained the relatively short lifetime of low energy electrons captured by the DNA, while similar studies performed with peptide nucleic acid (PNA), which consists of different backbone, result in long lifetime of the captured electrons and charging of the molecules.<sup>24</sup> Our new experimental methodology, based on real time Hall measurements combined with polarization and electrochemical experiments, allowed us to observe spin enhancement in electron transport through oxidatively damaged DNA. Our results strongly suggest that charge transmission in DNA not only is spin polarized, but follows two competitive paths characterized by different spin polarized efficiencies allowing implementation of a mechanism for transferring information on oxidatively damaged DNA. It is important to emphasize that the device used in this work has no ferromagnetic elements and therefore is not biased towards a specific spin eliminating magnetic field-related artifacts.

## ASSOCIATED CONTENT

### Supporting Information

(The Supporting Information is available free of charge on the ACS Publications website).

Supporting Information contains the details of GaN/AlGaN Hall device preparation using photolithography and techniques to grow DNA monolayer. Additionally there are some study on monolayer growth using PMIRRS and AFM. Details study of Enantioselective electrochemistry using chiral ferrocene have been provided. (damaged\_DNA\_SI.pdf)

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### Author Contributions

#Authors contributed equally.

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