Noise and sensitivity characteristics of solid-state nanopores with a boron nitride 2-D membrane on a pyrex substrate†

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We have fabricated highly sensitive and low noise solid-state nanopores with multiple layers of boron nitride (BN) membranes transferred onto a pyrex substrate. Both the dielectric and flicker noise of the device, which have been described as one of the bottlenecks to making highly sensitive 2-D membrane nanopore devices, have been reduced as follows. Firstly, a pyrex substrate with a low dielectric constant (εr = 4.7–5.1) and low dielectric loss (D < 0.001) is used instead of a Si substrate to reduce the dielectric noise of the device. Secondly, flicker noise is minimized by employing a 100 nm thick SiNx supporting layer with a small opening (less than 100 nm) for BN membrane transfer to enhance the mechanical stability. The flicker noise is further reduced by transferring multiple layers of BN instead of a single layer of BN. The resulting multi-layered BN device shows significant reduction of dielectric and 1/f noise as compared to the devices with a single layer of the BN and Si substrate. Furthermore, we demonstrate dsDNA translocations with a high signal to noise ratio around 50 at 100 and 10 kHz bandwidths.

Introduction

Considerable progress has been made recently with biological nanopores for single nucleotide identification1 and plausible DNA sequencing.2–4 This progress has resulted from the advantages inherent to biological nanopores, such as (a) reproducible formations of extremely small pore sizes (less than 1.5 nm), (b) extremely small thickness sensing zones (approximately 1 nm or less depending on protein utilized), (c) excellent low noise levels of the protein nanopore with less than 10 pA Irms, (d) controlling the DNA translocation speed using enzymes, and (e) relatively small interactions between the DNA and protein pore wall (infrequent sticking or clogging of DNA to the pore wall). On the contrary, the progress in solid-state nanopores has been much slower due to the lack of such advantages of protein nanopores. Still, solid-state nanopores are an attractive alternative because of their long term stability and versatility. Solid-state nanopores can be operated in harsh environments, be produced in a scalable manner, and can be engineered to act as an active device by itself or integrated with other sensing mechanisms.5–7

The basic structure of solid-state nanopores and their operating mechanism are almost the same as those of biological nanopores. A thin membrane with a nanometer scale pore provides a structure to sense biomolecules on a single molecule level by electrically trapping and translocating them through the pore.5 Here, the structure is utilized as a resistive pulse sensor to monitor the transient reduction of the pore conductance and time of reduction when the analyte biomolecules are electrophoretically driven through the pore. Until now, a wide range of analytes have been studied with solid-state nanopores, most commonly single- and double-stranded DNA, RNA, and proteins, as well as the interaction between these molecules.6–8 Still, various hindrances remain for the successful application of solid-state nanopores for biomolecule detection in general and, in particular, for DNA sequencing. These issues include (a) controlling the translocation speed of the biomolecule, (b) improving the trapping probability, and (c) enhancing both the spatial (lateral and vertical) and temporal resolution of the device.

In particular, the application of atomically thin two-dimen- sional materials such as graphene,19–22 boron nitride (BN)23,24 as well as the recently developed transition metal-chalcogenide of MoS2,25–27 as a membrane is an attractive method to improve the vertical resolution of these devices. For instance, to sequence DNA using solid-state nanopores, the vertical
resolution of the device, namely, the thickness of membrane, should be less than 0.5 nm for a single base-pair resolution. Because the thicknesses of a single layer of graphene, BN, and MoS₂ are approximately 0.3–0.7 nm, these are the ideal membrane materials for highly sensitive solid-state nanopore devices. Moreover, thinner membranes are expected to enhance the blockade signal to enhance the signal-to-noise ratio (SNR), assuming that the noise level is the same. However, the initial attempts of fabricating 2-D membrane nanopores using graphene were not satisfactory due to the high flicker noise that resulted. High flicker noise has also been obtained from other 2-D membrane materials such as BN and MoS₂, which showed flicker noises about two orders of magnitude higher than Si₃Nₓ membranes. Initially, the hydrophobic nature of the 2-D membrane material and structural defects in the membrane, such as pinholes and domain boundaries, were suggested as the source of this high flicker noise. However, recent reports by Kumar et al. and Heerema et al. reveal that the flicker noise level can be greatly reduced using fewer graphene layers instead of a single layer, which suggests that the mechanical stability of the membrane might be the major source of the flicker noise. Similarly, other researchers found out that decreasing the opening area of the supporting layer for the 2-D membrane effectively reduces the flicker noise in both graphene and BN. All of these results suggest that the mechanical stability of the membrane material is indeed one of the major factors that influence the flicker noise.

In this manuscript, we would like to present the fabrication scheme of a highly sensitive, low noise solid-state nanopore device using a hexagonal-BN (h-BN) membrane. Hexagonal-BN layers are insulators with a wide band gap (~5.9 eV), unlike the graphene which is a conductor. Additionally, h-BN nanopores are highly resistant to oxidation and turned hydrophilic by UV-oxygen treatments. Both these attributes are important considerations in the search for solid-state nanopore membrane materials. First of all, h-BN membranes were transferred onto two different substrate materials, Si and pyrex substrates, to compare the dielectric noise. Previously, we reported that the dielectric noise of the solid-state nanopore can be significantly improved by using a pyrex substrate instead of a Si substrate due to the low capacitance and dielectric loss of the pyrex substrate. Again, in this work, pyrex-based BN pores exhibit two orders of lower dielectric noise level than Si based, and the reduced dielectric noise permits sub 5 pA root mean square (RMS) noise level at 10 kHz frequency. The flicker noise level was compared using a single layer of h-BN versus multiple layers of h-BN. Here, the membrane layer(s) was transferred onto a 100 nm thick Si₃Nₓ supporting layer with only about an 80 nm opening area diameter. It is shown that the flicker noise power is two orders of magnitude smaller when using multiple layers of BN than when using a single layer.

Finally, we demonstrate how the DNA translocation signal varies with the filter frequency (10 kHz versus 100 kHz) for the translocating signals of a 1 kbp double-stranded DNA. The resulting 2D devices enable a sufficient noise level to measure dsDNA translocation events with a 100 kHz filter frequency. The dsDNA translocation signal appears quite different depending on the filter frequency employed, which shows the importance of improving both the spatial and temporal resolution of the nanopores.

Experiments

Pyrex substrate preparation

The fabrication process of the h-BN nanopores is schematically illustrated in Fig. 1a. Firstly, a low dielectric noise substrate of pyrex was prepared. The details of the device fabrication process were reported in our previous studies. Briefly, a 200 nm thick a-Si film was deposited on the top and bottom surfaces of a pyrex substrate by low pressure chemical vapor deposition (LPCVD). Then, an a-Si layer was lithographically defined and dry etched while the pyrex substrate was wet-chemically etched using diluted HF until a microchannel was vertically formed through the substrate. The resulting structure formed a 2 μm circular opening on the top-side of the a-Si layer (Fig. 1b). Then, a LPCVD Si₃Nₓ membrane with 100 nm thickness was transferred onto the pyrex substrate, and a sub-100 nm hole was drilled in the Si₃Nₓ membrane by a focused ion beam (FIB; Carl Zeiss, AURIGA). This layer acted as a mechanical supporting layer for the BN membrane. We tried to reduce the area of the opening of the Si₃Nₓ membrane because the mechanical stability of the membrane (or free standing area) is quite important in reducing the flicker noise level.

BN film preparation

Multiple layers of hexagonal-BN (h-BN) films were grown by chemical vapor deposition (CVD) on the Cu foil (Alfa Aesar, 125 μm thickness) using ammonia borane (NH₃-BH₃) as the source gas. The h-BN film grown under this condition was identified to have 6–8 layers by cross-sectional TEM analysis. The h-BN films were then transferred onto the Si₃Nₓ supporting layer by a PMMA coating, wet-chemical etching of the Cu foil, and PMMA cleaning with an annealing process. Fig. 1d shows that the Raman peak of the h-BN appears at 1366 cm⁻¹, which agrees with the published B–N vibration mode (E₂g). The XPS data also show that the binding energies of N 1s and B 1s are 397.8 eV and 190.3 eV, respectively, which are very close to the reported values of the CVD grown h-BN film (Fig. 1e).

Once the BN membrane was transferred onto the Si₃Nₓ/pyrex sample with a sub-100 nm hole in the Si₃Nₓ, a nanometer-size pore was drilled in the BN membrane by using a transmission electron microscope (TEM; JEOL JEM 2100F) with the pore size ranging from 3 to 12 nm.

Nanopore measurements

Before the ionic current measurements of the BN nanopores, the sample was treated with oxygen plasma (PELCO easi-Glow™) at a 0.2 mbar working pressure and 15 mA plasma current for 5 min, similarly to the UV-oxygen treatment of the
BN layer, to enhance the wettability of the sample. Then, the nanopore chip was mounted on a microfluidic flow cell with a PDMS gasket, and both chambers were filled with a 1 M KCl electrolyte and TE buffer solution (10 mM Tris-HCl and 1 mM EDTA buffer, pH 8.0). The Ag/AgCl electrodes were inserted into both chambers, and the two electrodes were connected to an Axopatch 200B amplifier with a 250 kHz sampling rate and low pass four-pole Bessel filter at 10 kHz or 100 kHz. For the dsDNA experiments, 1 kbp Fermentas NoLimits DNA fragments (Thermo Scientific) were used and 1 nM of dsDNA was inserted into the cis-chamber.

Results and discussion

Ionic conductance measurements

Fig. 2 shows representative TEM images of nanopores fabricated on multiple layers of the h-BN film with sizes ranging from 3 nm to 8 nm (Fig. 2a) and the corresponding I–V curves were measured from −200 mV to 200 mV (Fig. 2b). The ionic current clearly shows a linear ohmic behavior in the voltage ranges that were measured. In Fig. 2c, the pore conductance value is plotted with respect to the pore diameter. It is known that the pore conductance depends on the pore diameter and thickness of the membrane when the effect of the surface charge is negligible due to the high electrolyte concentration.

\[
G_{\text{nanopore}} = \frac{\sigma_{\text{KCl}}}{4L_{\text{eff}}/\pi D^2 + \frac{1}{D}}
\]

where, \(\sigma_{\text{KCl}}\) is the conductivity of the electrolyte solution (11.1 S m\(^{-1}\) for 1 M KCl), \(L_{\text{eff}}\) is the effective thickness of the membrane and \(D\) is the pore diameter. The first and second term in the equation imply that the channel resistance and access resistance contribute to the conductance. As is shown in Fig. 2c, the pore conductance follows a linear dependency on the pore diameter with an effective membrane thickness of \(L_{\text{eff}} = 1.4 \pm 0.2\) nm. Considering that our h-BN films have 6–8 layers with a physical thickness of 2.0–3.0 nm, this fitting value is in the reasonable range because the effective thickness is typically smaller than the physical thickness. Moreover, the linear dependency of the pore conductance on the pore diameter indicates that the pore conductance is mainly dependent on the access resistance, as is observed when the membrane thickness is smaller than the pore diameter.

Noise characteristics of BN nanopores

Each noise part of BN devices such as flicker and dielectric was improved in the following sequence. First, the dielectric
Noise was reduced by using a pyrex substrate instead of a Si substrate and then, the flicker noise by using multiple layers of h-BN instead of a single layer of BN; both were transferred to a SiN supporting layer with openings smaller than 100 nm. The noise characteristics of the nanopores were analyzed using the power spectral density (PSD, \( S_I \)) curve of the measured current traces and the RMS noise (\( I_{\text{RMS}} \)) obtained from the integration of the PSD with respect to the frequency up to the filter frequency. Here, the power spectral density (\( S_I \)) and the RMS noise (\( I_{\text{RMS}} \)) are expressed as the sum of four different noise sources as follows:

\[
S_I = S_{\text{Flicker}}(\propto 1/f) + S_{\text{Thermal}}(\propto 1/R_P) + S_{\text{Dielectric}}(\propto C_D D_\Omega f) + S_{\text{Amp}}(\propto f^2)
\]

\[
I_{\text{RMS}}^2 = \int S_I df,
\]

\[
I_{\text{RMS}}^2 = I_{\text{Flicker}}^2(\propto \ln(f)) + I_{\text{Thermal}}^2(\propto f/R_P) + I_{\text{Dielectric}}^2(\propto C_D D_\Omega f^2) + I_{\text{Amp}}^2(\propto f^3)
\]

where, \( f \) is the frequency, \( R_P \) is the pore resistance and \( C_D \) and \( D_\Omega \) are the capacitance and dielectric loss of the nanopore device.\(^{35,36}\) The four noise sources are the flicker noise (\( S_{\text{Flicker}} \)), thermal noise combined with shot noise (\( S_{\text{Thermal}} \)), dielectric noise (\( S_{\text{Dielectric}} \)) and amplifier noise (\( S_{\text{Amp}} \)), and each source has a specific frequency dependency.

Here, three different types of BN nanopore device structures were prepared to investigate the effect of the structural distinction on the noise properties: ① multiple-BN/SiN\(_x\)/pyrex ② single-BN/SiN\(_x\)/pyrex ③ single-BN/SiN\(_x\)/Si, where multiple-BN and single-BN are multiple layers of BN and single layer of BN (Graphene Supermarket).

**Noise comparison with Si and pyrex substrate.** To investigate the impact of the substrate material, the ionic current noise of a single-BN membrane nanopore fabricated on a conventional Si substrate was compared to that of a single-BN nanopore on a pyrex substrate. Fig. 3a shows 2-second ionic current traces measured at 0 mV and 100 mV of (a) a single-BN on Si (red), (b) a single-BN on a pyrex substrate (blue), as well as (c) a multiple-BN on a pyrex substrate, with a pore diameter of approximately 4 and 5 nm. In addition, Fig. 3b and c show the corresponding power spectral density (PSD) curves obtained at 0 and 100 mV, respectively. All the data shown in Fig. 3 were obtained at a 250 kHz sampling frequency and were filtered at 10 kHz.

First of all, the pyrex-based single-BN pore considerably exhibits the low dielectric noise (Fig. 3b) due to the low capacitance and dielectric loss of the pyrex substrate (5–10 pF in 1 M...
KCl). The dielectric noise level of a pyrex-based device is $3 \times 10^{-8} f (pA^2 Hz^{-1})$, which is two orders of magnitude lower than that of the Si-based device $5 \times 10^{-6} f (pA^2 Hz^{-1})$. Because of this large difference, the pyrex-based single-BN pore had a lower RMS noise, 3.6 pARMS, while the Si-based single-BN pore had 28 pARMS measured at 0 mV. When voltage is applied across the pore and the ionic current is measured, flicker noise ($1/f$) is generated as a function of applied voltage (or ionic current), $S_{\text{Flicker}} = (A_N f)^{1/2}$, where $A_N$ is the noise power and $I$ is the ionic current.37 For instance, Fig. 3c shows the PSD of the devices measured at 100 mV. Here, both devices (single-BN/pyrex and single-BN/Si) show similar $1/f$ noise, where each fitting value is $36f^{1.15}$ and $86f^{1.15}$ (pA^2 Hz^{-1}) for the pyrex and Si-based materials from the curve fitting with the function $S(f) = A f^\beta$ (where $A$ is fitting parameter and $0 < \beta < 2$, where parameter $\beta$ is commonly close to 1). The slight discrepancy of the $1/f$ noise level appears to be caused by the difference in the pore conductance of the two type of pores, where the conductance of a single-BN/Si device ($G = 68$ nS) is slightly higher than that of the single-BN/Py device ($G = 43$ nS). Fig. 3d shows the corresponding frequency response of $I_{\text{RMS}}$ describing the contribution of each noise source to the total RMS value. The $I_{\text{RMS}}$ curves have the plateau over the filter frequency, in this graph, 10 kHz. The applied voltage (100 mV) across the pore amplified the RMS noise level to 36 pARMS for the Si-based device and to 15 pARMS for the pyrex-based device. The dotted lines in Fig. 3d are the theoretically calculated dependency of $1/f$ noise (green) on the thermal + dielectric noise (purple). The single-BN pyrex sample exhibited a similar trend to the flicker noise dependency, which means that only the $1/f$ noise contributed to the total RMS noise. On the other hand, the flicker noise component of the single-BN/Si sample was dominant only up to 3000 Hz, and the remaining frequency domain was governed by the dielectric noise. Thus, the $I_{\text{RMS}}$ values of the two pores showed a similar interval as the applied voltage increased from 0 mV to 200 mV in the $I_{\text{RMS}}$ versus voltage curve (Fig. 3f), where the slope of this curve means the $I_{\text{RMS}}$ dependency on the $1/f$ noise, and the $I_{\text{RMS}}$ of both pores shows the proportional scaling to the applied voltage with a similar slope. In other words, the $I_{\text{RMS}}$ of a single-BN pyrex pore shows lower values compared to that of a single-BN/Si pore because the latter is affected by the high dielectric noise as well as the $1/f$ noise in the voltage range we measured.

**Noise comparison with single and multiple-BN.** Now we will turn our attention to the comparison of single-BN versus mul-
multiple-BN membrane with regard to the flicker noise. Fig. 3a–c describe the current traces and PSD curves of single-BN (blue) and multiple-BN (green) on a pyrex substrate at 0 mV and 100 mV. Both the single-BN and multiple-BN pores show a very close ionic current noise at 0 mV (3.6 pARMS and 4.3 pARMS, respectively). The PSD graph at 0 mV illustrates that the multiple-BN pores (ϕ 8 nm, G = 79 nS) have a slightly higher thermal noise floor than the s-BN pore (ϕ 4 nm, G = 43 nS) because the thermal noise is proportional to the conductance (S_ther = 4kT/R_pore = 4kT/G_pore). Again, when voltage was applied, flicker noise was generated and the noise level goes up to 15 and 6.8 pARMS for the single-BN and multiple-BN based devices. As shown in Fig. 3c, the 1/f noise level of the multiple-BN based device (2.3/pA^2 Hz^-1) was one order of magnitude lower than that of the single-BN based device (36/pA^2 Hz^-1). The 1/f noise levels of our multiple-BN nanopores ranged from 1/f to 10/f magnitudes (pA^2 Hz^-1) at 100 mV, depending on the pore size (Fig. S1, ESI†). Fig. 3e shows the normalized power spectral densities (S_f/I^2) of the single-BN and multiple-BN nanopores to compare the noise power A_N, which is independent of the current and applied voltage. The PSD of each pore was converted to the normalized PSD with three different voltages, and each of the normalized PSD curves overlap the same range of magnitudes. Each spectrum was fitted to the following relation, S_f/I^2 = A_N/f to find the value of noise power. The fitting result of A_N was 1.3 × 10^-6 (dimensionless) and 3.7 × 10^-8 for the single-BN and multiple-BN pore, respectively.

The A_N value of the multiple-BN nanopores varied from 7.6 × 10^-7 to 2.1 × 10^-8 as the pore diameter changed from ϕ 4 nm to 12 nm. Table S1† shows the previously reported values of A_N. Considering the pore size tested, our value of A_N (3.7 × 10^-8 for 8 nm pore size, 2.1 × 10^-8 for 12 nm pore size) was one order lower than the reported BN pore with ϕ 10 nm (6.7 × 10^-7).24 Additionally, our value is comparable to the A_N value of typical SiNx pores (5 × 10^-8).29,37 This indicates that multiple-BN pores combined with the small opening area in the SiNx supporting layer and improved the noise level in response to the applied voltage. This result agrees with the recently published results of flicker noise reduction with increasing graphene layer thicknesses15,16 and small opening window sizes,23,24 which is explained by the enhancement of the mechanical stability. In Fig. 3f, the influence of the applied voltage on the I_RMS is investigated in the corresponding single-BN and multiple-BN device by varying the voltage from 0 to 200 mV. Fig. 3f shows that the I_RMS values of the multiple-BN based pore have a much lower voltage dependency than those of the single-BN based pore, where the slope of the former is about four-times lower than that of the latter. This slope discrepancy is well matched with the difference in the 1/f noise level of the single-BN and multiple-BN pores, considering the relationship I_RMS^2 = ∫ S_f df. As a result of the low 1/f noise dependency, the multiple-BN nanopores showed approximately 10 pARMS even at 200 mV.

**Noise comparison with 10 kHz and 100 kHz.** The high bandwidth for nanopore measurements is required to detect accurate current blockades, but increasing bandwidth is accompanied by increasing noise and decreasing SNR. To explore the possibility of high bandwidth, the noise characteristics of the multiple-BN pore on a pyrex substrate were measured at 100 kHz bandwidth and compared with that at 10 kHz filter frequency. As an example, Fig. 4a shows the PSD plot of the ϕ 8 nm multiple-BN pore at 0 and 100 mV, filtered at 10 kHz (green) and 100 kHz (red). The PSD curves were dampened in the region of each filter frequency. The spectral densities of the 100 kHz filter show a thermal noise floor combined with a low dielectric noise and are located in the 10^-2 and 10^-3 pA^2 Hz^-1 region at 10^2 to 10^5 Hz frequencies.

Fig. 4b shows the increase in the I_RMS value by the existing thermal and dielectric noise in the 10–100 kHz bandwidth as observed in the theoretical fits. Thus, the difference in the I_RMS values using the 10 kHz and 100 kHz filter frequencies is

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**Fig. 4** (a) Power spectral densities of m-BN pore on pyrex under 0 mV and 100 mV, filtered at 10 kHz (green colors) and 100 kHz (red colors). (b) RMS noise versus frequency curves of the same pore for 10 kHz and 100 kHz filter under 100 mV, as described in panel a. The black dotted line results from the theoretical fits and it can be split into flicker and other noise part. (c) RMS noise of the corresponding m-BN pore with 10 kHz and 100 kHz against the applied voltages up to 200 mV.
almost the same, approximately 8 to 10 pA, and independent of the applied voltage. Although this device showed an RMS noise increase of approximately 10 pA with a 100 kHz filter, the noise level was still below 20 pA\textsubscript{RMS} at 200 mV, which provides sufficient noise level to detect biomolecule translocations.

**Double-stranded DNA transport**

The translocation events of the 1 kbp ds-DNA through the Φ 4 nm multiple-BN pore (25 nS) were measured at different filter frequencies (100 kHz and 10 kHz). The electrolyte solution was 1 M KCl with 10 mM Tris and 1 mM EDTA (pH 8.0), and the concentration of the dsDNA was adjusted to 1 nM. To see the bandwidth effect, 1 kbp ds-DNA was selected for this experiment because the mean translocation time of this size of DNA was reported to locate in 10 μs (100 kHz filter frequency) to 100 μs (10 kHz filter frequency). Fig. 5a shows the continuous ionic current traces measured with 150 mV (black), 200 mV (red) and 250 mV (blue), filtered at 100 kHz. Also, data-sets of 10 kHz filter frequency are displayed in Fig. S2.†

From the ionic current traces, the actual DNA translocation events were selected to exclude bouncing or collision spikes. For instance, the histogram of all current drops at 200 mV is shown in Fig. S3a† which typically shows two Gaussian distribution. Here, we regard the first Gaussian as bouncing spikes and the second Gaussian as real translocation events. Indeed, both \( t_d \) and \( \Delta I \) of the bouncing spikes are independent of the applied voltage (Fig. S3b†) indicating that these are not the actual translocation events. So, only the events involved in Gaussian distribution of translocations were selected and exhibited in the scatter plots.

The scatter plots for the blockade current (\( \Delta I \)) and dwell time (\( t_d \)) with 150 mV, 200 mV, and 250 mV of the applied voltage are summarized in Fig. 5b (100 kHz filter) and Fig. S2b† (10 kHz filter). It is noted that the mean blockade currents filtered at 10 kHz look about two times lower than the ones filtered at 100 kHz under all the voltage conditions. For instance, the mean blockade current measured at 10 kHz varies from 350 to 550 pA with applied voltages of 150–250 mV, while it varies from 600 to 1100 pA when measured at 100 kHz in the same applied voltage range. This tendency means that the translocation events at 10 kHz were distorted due to the relatively short translocation time. In fact, it is known that the signal for fast single molecule events below the temporal resolution is notably attenuated.38 As is shown in Fig. S3b†, the mean dwell time of the 1 kbp ds-DNA translocation measured at 100 kHz was approximately 45, 29 and 23 μs at the applied voltages of 150, 200, and 250 mV, respectively, which is smaller than the temporal resolution of the 10 kHz filter (100 μs). To support this, Fig. S4a† shows a 30 s continuous current trace measured with the 100 kHz filter (blue) as well as those digitally filtered to 10 kHz (red) using an 8 pole Bessel filter. In addition, Fig. S4b† represents an example of 7 DNA translocation events where the translocation time varied from 20 to 200 μs. This is shown to demonstrate how the electrical filter distorts the blockade signal when \( t_d \leq 2 \tau \text{rise} \), where \( \tau \text{rise} \) is the finite rise time of the filter and is related to the filter frequency \( f_c : \tau \text{rise} \approx 0.33/f_c \) (≈ 33 μs for 10 kHz filter).36,39 Accordingly, the first four events with a \( t_d \) less than 66 μs (≈ 2 \( \tau \text{rise} \)) were clearly attenuated by the 10 kHz filter while the DNA events longer than 66 μs were not.

The normalized histograms of \( \Delta I \) with three different voltages are shown in Fig. 5c (100 kHz). The mean \( \Delta I \) values obtained from a Gaussian fitting are shown with respect to the applied voltages in the inset of Fig. 5c. As expected, the \( \Delta I \) shows a linear dependency on the applied voltages and the slope of the linear fitting matches the blockade conductance \( \Delta G \) (\( \Delta I = \Delta G \)). The measured blockade conductance for 1 kbp dsDNA was 4.3 ± 0.2 nS at 100 kHz. This is the comparable value to \( \Delta G \) of single layered graphene nanopore with a 4 nm diameter, which is ~4.8 nS when scaled to 1 M KCl (\( \Delta G \sim 12 \text{nS in 3 M KCl} \)).22 In Fig. S2c,† the measured \( \Delta G \) at 10 kHz was distorted to 2.3 ± 0.1 nS and about two times lower than that at 100 kHz.

Fig. 5  (a) Ionic current traces for 1 kbp dsDNA translocation at 150 mV (black), 200 mV (red) and 250 mV (blue) through Φ 4 nm m-BN nanopore in 1 M KCl with TE buffer (pH 8.0), filtered at 100 kHz. Each trace is measured during 10 s. (b) Scatter plots of blockade current (\( \Delta I \)) and dwell time for different voltages. The inset is blockade current level as a function of voltage, showing linear dependency of \( \Delta I \) on the applied voltage.
Finally, the signal to noise ratio (SNR = ΔI/I_{RMS}) was obtained with respect to the voltages from 150 mV to 250 mV with two different filters (Fig. S5†). Although the SNR measured at 100 kHz is lower than those at 10 kHz, our BN pore has a sufficient SNR value at 100 kHz bandwidth (from 40 to 55). This implies that we have a feasibility of applying high bandwidth more than 100 kHz with 1 MHz bandwidth equipment.40

Conclusions

The aim of this research was to improve the noise properties of BN nanopores. We developed the BN pore using a low-noise substrate platform and multi-layered BN membranes with small opening area. After comparing the effect of the substrate material, we demonstrated that our m-BN based devices had a lower 1/f noise level than the s-BN based devices. As a result of the reduced 1/f and dielectric noise, the multiple-BN pores had an ionic current noise level of 10 pA_{RMS} at 200 mV. Finally, we detected 1 kbp dsDNA translocation events through low noise m-BN nanopores with 100 kHz and 10 kHz filters. We also confirmed that the signal to noise ratio of this device was approximately 50 for both filters. Although we demonstrated simple double-stranded DNA transport with the m-BN pore in this manuscript, we anticipate that our developed BN nanopores, which have a high SNR, have the potential to identify the four base pairs of DNA and realize DNA sequencing, eventually.

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