A Three-State Nanofluidic Field Effect Switch

Marie Fuest, Caitlin Boone, Kaushik K. Rangharajan, A. Terrence Conlisk,* and Shaurya Prakash*

Department of Mechanical and Aerospace Engineering, The Ohio State University, Columbus, Ohio 43210, United States

Supporting Information

ABSTRACT: We report a three-state nanofluidic field effect switch in an asymmetrically gated device with a forward (positive), off (zero), and a reverse (negative) current state for tunable control of ionic transport by systematically controlling the gate potential. The embedded gate electrode allows for modulation of the ionic current through the 16 nm deep channels as a function of electrolyte concentration and gate electrode location for a fixed streamwise potential.

KEYWORDS: nanofluidics, field effect, nanochannel, gating, fluidic transistor, fabrication

Nanofluidic field effect devices, analogous to semiconductor field effect transistors, feature a nanofluidic channel with a “gate” electrode embedded in the nanochannel wall for systematic manipulation of the surface potential at the dielectric–electrolyte interface.1,2 The gate electrode is isolated from the aqueous electrolyte in the channel by a dielectric layer. An axial or streamwise potential applied between the inlet and outlet of the nanochannel drives streamwise transport of ions through the nanofluidic channel.3–5 An independently controlled applied voltage to the gate electrode allows active, tunable control over the local surface potential in the nanofluidic channel. Taking advantage of the nanoscale geometry, the local change in potential penetrates through the entire nanoscale depth of the channel5 permitting active and reconfigurable control7 over the concentration of charge carriers, or net space charge density, in the fluid volume.8,9 This active control over the concentration of ionic species modulates electrokinetic flows as measured by changes in current through the nanofluidic architecture (nanopore or nanochannel).7,8,10–13 An increase in current indicates a higher concentration of charge carriers flowing through the nanochannel and a decrease in current indicates a lower concentration of charge carriers flowing through the nanochannel.7,8

Nanofluidic field effect transistors, or flow-FETs, have been proposed as the basis for ionic circuits,8,14 with the goal of performing detailed logic functions similar to solid-state circuits for controlled transport of ionic species in small volumes (nanoliter or less) of fluid. Many technological demonstrations have shown manipulation of ions and biomolecules at femtoliter volumes8 for biosensing,15,16 sample concentration,17 molecular sorting,18 and separations19–20 moving toward the still elusive goal of performing controlled ion transport functions similar to biological systems.7,21–23 Most advances in development of ionic circuit elements have focused on ionic diodes and current rectifiers24–30. Nearly all nanofluidic diodes operate in a fixed rectification regime with no changes possible to rectifying properties after device fabrication. A recent demonstration of tunable, reconfigurable rectification with a nanofluidic field effect device demonstrates the advantage of using flow-FET devices for building elements of ionic circuitry.7 In contrast to diodes that permit flow of current and therefore ions in a preferential direction, based on the axial potential direction, current switching, or the ability to switch the current “on” and “off” arising from gate control for fixed axial potential has not yet been reported. Switching or flow gating is a key advance required for ionic circuits in moving toward fluidic logic control as well as specific applications such as artificial ion channels.15,31

This letter reports on the implementation of a nanofluidic field effect device with 16 nm deep channels as a current switch controlled by systematically manipulating the potential applied to the gate electrode. All measured current states were referenced with respect to the ungated case, that is, the case where only an axial potential was applied but no gate potential was applied. The device reported in this paper is in an asymmetric configuration (Figure 1), with details discussed later. A positive current increasing with applied gate voltage (forward state) and a negative measured current (reverse state) for a fixed axial voltage were observed in addition to a device state where the measured current was nearly zero (off state) during the gating of the nanofluidic device. Therefore, the purpose of this letter is to demonstrate the operation of a nanofluidic field effect switch controlled by a gate electrode across a broad range of experimental parameters.

In recent years, several other reports have demonstrated the complexity and challenges in fabricating gated nanochannels with insulated gate electrodes.8,10,11,32,33 We developed an alternate fabrication sequence5 for gated nanofluidic devices that relies on photolithography, wet etching, and oxygen plasma bonding techniques34–36 to yield a sealed nanofluidic device. The nanofluidic device consists of two microfluidic channels as

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Figure 1. (A) Schematic showing an exploded view of the fabricated field effect nanofluidic device. The fluidic network consisted of two 10 μm deep × 50 μm wide × 3.2 cm long microchannels connected by a bank of three 16 nm deep × 30 μm wide × 5 mm long nanofluidic channels wet-etched into borosilicate glass. Gold gate electrodes (20 nm high × 25 μm wide) were patterned on a second glass substrate (cover) and bonded to the substrate with the channel network using an intermediate PDMS layer. The PDMS layer isolated the gate electrodes from the substrate. The complete nanochannel width of 30 μm does not permit imaging the entire cross section in one frame. From the SEM image, the PDMS dielectric layer was measured to be ∼500 nm thick. The cut-line along the nanochannel inlet as indicated in the schematic by the red dash-dot line on the full device schematic (Figure 1A). The device featured six individually addressable gate electrodes with each electrode location given by the relative distance of the center of the electrode from the nanochannel inlet as indicated in the schematic by $L_i$.

Fluidic reservoirs for a bank of three 16 nm deep × 30 μm wide × 5 mm long nanofluidic channels etched in borosilicate glass (Figure 1). The low aspect ratio of the nanofluidic channels (depth ≪ width) enables nanoscale effects similar to biological systems while providing high throughput and benefits of 1-D theoretical analysis. Gold (Au) gate electrodes (20 nm high × 25 μm wide) were patterned on a second glass substrate that acts as a cover for the etched channels (Figure 1A). The Au gate electrodes were asymmetrically placed along the length of the nanofluidic channel to allow investigation of the effect of electrode location on the field effect control, or current modulation. A polydimethylsiloxane (PDMS) layer spun over the Au electrodes isolated the gate electrodes from the electrolyte within the nanochannels and provided a surface for bonding the two substrates (one with channel features etched in borosilicate glass and the cover with the isolated gate electrodes). Detailed fabrication procedures for the channel networks and device bonding were reported previously. A schematic showing the exploded view of the fabricated device is shown in Figure 1A. A scanning electron microscope (SEM) image of the nanochannel cross section is shown in Figure 1B, showing the PDMS dielectric layer was ∼500 nm thick. The exploded side view schematic (Figure 1C) shows the glass cover with asymmetrically spaced Au gate electrodes isolated from the fluid by a PDMS dielectric layer. The cut-line along $A'$ was used to generate the side view schematic and is indicated by the red dash-dot line on the full device schematic (Figure 1A). The device featured six individually addressable gate electrodes with each electrode location given by the relative distance from the nanochannel inlet to the center of the gate electrode (see Supporting Information Figure S1). In this work, only one of the six electrodes was active at a given time and the results are described in the sections to follow.

In line with previous reports, electrolyte solutions of KCl in DI (deionized) water at concentrations varied between 0.1 mM to 100 mM at pH 7 ± 0.2 were used as the working fluid. A potential difference between the two microchannel reservoirs (axial potential, $V_a$), drives flow through the nanofluidic channels as shown schematically in Figure 1D. The net direction of fluid flow for the ungated case ($V_g = 0$ V) is marked by the red arrow. The axial and gate potentials are referenced to the same ground. The location of a given electrode is the relative distance of the center of the electrode from the nanochannel inlet as indicated in the schematic by $L_i$. The low aspect ratio of the nanofluidic channels (depth ≪ width) enables nanoscale effects similar to biological systems while providing high throughput and benefits of 1-D theoretical analysis. Gold (Au) gate electrodes (20 nm high × 25 μm wide) were patterned on a second glass substrate (cover) and bonded to the substrate with the channel network using an intermediate PDMS layer. The PDMS layer isolated the gate electrodes from the fluid in the nanochannels. (B) Scanning electron microscope (SEM) image of the bonded nanochannel cross section. The complete nanochannel width of 30 μm does not permit imaging the entire cross section in one frame. From the SEM image, the PDMS dielectric layer was measured to be ∼500 nm thick. The cut-line along the nanochannel inlet as indicated in the schematic by the red dash-dot line on the full device schematic (Figure 1A). The device featured six individually addressable gate electrodes with each electrode location given by the relative distance of the center of the electrode from the nanochannel inlet to the center of the gate electrode (see Supporting Information Figure S1). In this work, only one of the six electrodes was active at a given time and the results are described in the sections to follow.

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dielectric layer was also measured to confirm adequate electrical isolation of the gate electrodes in accordance with previous reports for gated nanochannels (Supporting Information Figure S2 and S3).\textsuperscript{7,10,32,33}

The nanofluidic device was first operated with $V_g = 0$ V, also referred to as the ungated case. Nanochannel conductance, $G$, given by the ratio of the measured current to applied axial potential ($I/V_a$), follows a linear trend for high concentrations ($\geq \sim 1$ mM) as expected from bulk fluid conductance.\textsuperscript{1,7,8,10,40} At low concentrations ($\leq \sim 1$ mM) conductance has nearly a constant value (Figure 2), indicating the surface charge governed regime.\textsuperscript{8,10,40,41} To maintain electroneutrality, the net charge in the nanochannel volume must be equal and opposite to the total charge on the nanochannel walls. The number of charge carriers in the nanofluidic channel, and therefore, the conductance is determined by the surface charge at low concentration. The critical concentration where the transition between the bulk transport and surface charge governed transport occurred was $\sim 1$ mM in agreement with trends reported previously.\textsuperscript{7,8,40}

The height of the bonded nanofluidic channels was estimated from the conductance data in the bulk conductance or high concentration range.\textsuperscript{7} The estimated height from conductance data was 18 nm where the bulk conductance for three 18 nm deep, 30 $\mu$m wide, 5 mm long nanochannels is plotted in Figure 2 indicated by the solid black line. The equation for the bulk conductance is presented in the Supporting Information. The estimated depth is in reasonable agreement with atomic force microscopy measurements that showed the nanochannel depth before bonding was 16 nm $\pm$ 1 nm.\textsuperscript{5}

Applying a gate voltage causes a change or modulation of measured current through the nanofluidic device with respect to the ungated case ($V_g = 0$ V). As a representative case, current through the nanochannels as a function of the gate voltage for 1 mM KCl solution at an axial potential of 3 V is reported in Figure 3A. The gate electrode was positioned at 0.57 $L$, where $L$ is the total length of the nanochannel (Figure 1D).

As the gate voltage was swept from 0 V to $−2$ V the measured current decreased until the current was switched off, that is, no measurable current was recorded at $V_g = −1.4$ V with $V_a$ still at 3 V. Changing the gate voltage from $−1.4$ V to $−2$ V reversed the polarity of the measured current with a current of $0.026$ nA for $V_a = 3$ V and $V_g = −2$ V. Therefore, the device has three states of operation with respect to the ungated case; a forward current, an off or zero current case, and a reverse current state for a fixed axial potential.

To our knowledge, this device presents the first demonstration of current switching in a nanofluidic field effect configuration, with tunable control over both the magnitude and direction of current. Figure 3B shows repeatable on–off operation of the nanofluidic field effect switch. For fixed axial potential, the gate voltage can be tuned to modulate the current to the desired value. For example, in Figure 3B the applied voltages for 0.1 mM KCl were cycled from $V_a = 3$ V, $V_g = 0$ V producing $0.024 \pm 0.002$ nA of current to $V_a = 3$ V, $V_g = −3$ V to switch off the current. Although the details on concentration dependence of measured current modulation with $V_g$ are discussed later, it is worth noting here that in the surface charged governed regime (typically with electrolyte concen-
tration \leq 1 \text{ mM for the ungated case}), controlling the gate potential allows switching of the current.

Using previously reported analytical models to explain the observed data trends for electrokinetically driven flow,\textsuperscript{7,10,42} the components of the current due to electromigration of $K^+$ and $Cl^-$ are given by

$$I_{K^+} = F \mu_{K^+} A [K^+] \bar{E}$$

and

$$I_{Cl^-} = -F \mu_{Cl^-} A [Cl^-] \bar{E}$$

where, $I_i$ is the current due to a species $i$, $\mu_i$ is the ionic mobility of species $i$, $A$ is the cross section area of the nanochannel, $[i]$ is the concentration of species $i$ in the nanochannel, and $\bar{E}$ is the electric field.\textsuperscript{7,42} The ionic mobility, $\mu_i$ is given by $z_i D_i F/RT$ where $z_i$ is the valence of species $i$, $D_i$ is the diffusion coefficient of species $i$, $F$ is Faraday’s constant, $R$ is the universal gas constant, and $T$ is the temperature.\textsuperscript{39} Note that the term in parentheses in the equations above is the flux of the ions under the influence of an electric field.\textsuperscript{42} Applying the previously reported assumption, $\mu_{K^+} \approx -\mu_{Cl^-}$, the total current due to the summation of the cationic and anionic contributions is given by

$$I_{\text{total}} = F \mu_{K^+} A ([K^+] + [Cl^-]) \bar{E}$$

The 5 mm long nanochannels (compared to 30 \textmu m width and 16 nm depth) are sufficiently long such that the electric field in the ungated case can be approximated as $E = V/g/L_n$, as has been reported previously for nearly 1-D nanochannels.\textsuperscript{43}

Consequently, any change in current for a finite gate potential compared to the ungated case will be caused by a change in the ionic concentration or a change in the electric field within the nanochannel, or both (eq 3). Since the gate electrode is known to induce a local change in the effective surface charge on the channel wall,\textsuperscript{9,44,45} to maintain overall electroneutrality of the system, the relative concentration of potassium and chloride within the nanochannel must change.\textsuperscript{7–9} Karnik et al.\textsuperscript{8} experimentally verified this relative change in concentration of ionic species through fluorescence measurements. The consequence of this change in relative species concentration is the modulation of the current due to increased or decreased availability of charge carriers.\textsuperscript{8,9} In addition to the change in the total number of charge carriers in the channel, it is likely with the gate voltage turned on, the local electric field modulation also causes a change in the local concentration, which will influence the flow of current. Further investigation of the nature of concentration profiles is needed.\textsuperscript{46} though past experimental work has also implied influence of concentration gradients on current profiles.\textsuperscript{7,44} which can include the possibility of negative current.

The change in concentration is often analyzed in terms of the charge stored by the gate electrode/dielectric/electrolyte capacitor,\textsuperscript{7,47} approximating the flow-FET as an equivalent electric circuit for analysis of data trends.\textsuperscript{5,7} In these previous reports, the electric field through the nanochannel is considered to be the same in the ungated and gated cases. Although change in the species concentration will result in current modulation and is required to maintain overall electroneutrality, given the sign of each term in eq 3 reversal of the current from positive to negative, as observed in Figure 3, requires a change in the direction of the electric field. The determination of the exact mechanism for this expected reversal of electric field within the nanochannel will likely require detailed numerical models as discussed below and is beyond the scope of this work. A hypothesis based on discussion of relevant literature and further device characterization is presented next.

Detailed numerical models have shown that the potential of the gate electrode can penetrate through the entire depth of the nanochannel.\textsuperscript{6,48} The gate electrode descreening model presented by Liu et al.\textsuperscript{6} suggests that ionic flux driven by the axial potential through the nanochannel along with high electric fields (on the same order as the thermal voltage) prevent the formation of an electric double layer (EDL) in the electrolyte region immediately below the gate electrode, leaving the gate electrode partially “descreened.” The result is a local region in the nanochannel with a potential proportional to the gate electrode that penetrates throughout the depth of the nanochannel. The partial descreening of the gate electrode is one proposed explanation for why experimentally observed current modulation exceeds predictions of capacitive or electric double layer based models.\textsuperscript{6,48} Additional numerical reports on two-dimensional analysis of gated nanofluidic channels have also shown that the electric field in the nanochannel is significantly more complicated by applying a potential to the gate electrode,\textsuperscript{9,44,45} than is captured by analytical models. The electric field throughout the nanofluidic architecture is a function of both applied axial and gate potentials as well as gate electrode location, which alters the impact of the field effect on the measured current.\textsuperscript{45,50} However, many challenges remain in numerically quantifying the effect of transverse electrostatics from the gate electrode on streamwise transport of ions and fluid for real nanofluidic effect devices.\textsuperscript{6,48}

In the present case, we hypothesize that the electrolyte region directly below the gate electrode is at some potential $\alpha V_g$. The variable $\alpha$ is an empirical parameter that accounts for potential change from the gated dielectric—electrolyte interface through the depth of the nanofluidic channel to the other physical wall of the device (see Supporting Information Figure S4 for a visual representation). It is likely that $\alpha$ depends on a variety of factors including dielectric material,\textsuperscript{6} dielectric thickness,\textsuperscript{7,45} gate electrode length,\textsuperscript{9,44,45} gate electrode position,\textsuperscript{9,44} and electrolyte concentration.\textsuperscript{6} As $\alpha \to 0$, the system approaches the previously reported capacitor model where the gate electrode modulates the ionic concentration in the channel but the electric fields in the gated and ungated cases are the same. Therefore, the change in potential within the nanochannel in the region below the gate electrode alters the electric field in the nanochannel and enables the switching behavior observed in Figure 3. As real dielectrics in nanofluidic field effect devices permit a finite gate leakage current,\textsuperscript{7,10,32,33,46,47,51,52} in addition to the capacitive coupling of the gate electrode and the nanofluidic channel, a finite gate leakage current was measured through the PDMS dielectric layer. Although the magnitude of the gate leakage current is smaller than the measured ion transport current (see Supporting Information) the presence of the finite gate leakage current may contribute to the alteration of the electric field,\textsuperscript{36} likely enhancing the effect of the gate electrode compared to the case of an ideal dielectric.

In order to further test the hypothesis that a change in electric field induced by the gate electrode is responsible for the observed three-state current switch, $V_{g} V_{e}$ and $L_n$ (center of gate electrode as measured from nanochannel inlet) were varied systematically and the subsequent effect on the measured current through the nanofluidic channels is reported. Figure 4 shows measured current at three values of axial potential ($V_x$).
For the representative case, KCl concentration was 1 mM and the gate electrode was located at 0.57 L. Interestingly, for all three values of $V_g$, the slope in Figure 4, $dI/dV_g$, remained constant with a value of 0.060 ± 0.003 nA/V. It is worth noting that in the same device for a given electrolyte concentration, the measured current can be switched off for different combinations of $V_a$ and $V_g$. In addition, current reversal was also obtained by systematically tuning $V_g$ with respect to $V_a$.

 Representative plot showing current modulation in a nanochannel filled with 1 mM KCl as a function of gate voltage for three test axial potentials. In all three cases the slope, $dI/dV_g$, remained constant with a value of 0.060 ± 0.003 nA/V. It is expected that the change in concentration required to maintain electroneutrality will depend on the magnitude and polarity of the gate voltage.9,10 The term $(K_{gated}^+|Cl_{gated}^-)$ is the concentration of potassium and chloride ions in the channel in the gated case. Upon application of a gate voltage, the concentration of species in the nanochannel will change to maintain overall electroneutrality.9,14 It is expected that the change in concentration required to satisfy electroneutrality will depend on the magnitude and polarity of the gate voltage.9,10 The term $(V_a/L)$ is the electric field in the nanochannel in the ungated case45 and the term $(aV_g/(L - L_1))$ is the contribution to the electric field from the gate electrode where $L - L_1$ is the distance from the gate electrode to the grounded microchannel. Note that for $V_g = 0$ V eq 4 becomes the ungated case with $[i] = [i_{ungated}]$. As $\alpha \to 0$ and $V_g \neq 0$, eq 4 approaches the capacitor model used in previous reports17, with the same electric field in the gated and ungated cases.

 From eq 4, the contribution to the electric field from the gate electrode has either an additive or subtractive effect when compared to the ungated axial field, as all potentials are applied with respect to the same reference. Application of a gate voltage will either enhance the effect of the axial voltage or reduce the effect, with the possibility of reversal in the electric field based on the relative magnitude and polarity of $(V_a/L)$ with respect to $(aV_g/(L - L_1))$. For example, in the case of a positive axial potential (i.e., $V_a = +3$ V) the contribution to the electric field from the gate electrode will be in the same direction as the axial field for a positive gate voltage ($+V_g$) leading to an increase in electric field and, therefore, forward current (Figure 5).

 Figure 5. Representative plot demonstrating that the current modulation depends on the additive or subtractive effect of the electric field induced by the gate electrode with respect to the axial field. The gate electrode was located at 0.57 L. For $V_g = +3$ V a negative gate voltage ($-V_g$) decreases the magnitude of the current while for $V_g = -3$ V the same negative gate voltage ($-V_g$) increases the magnitude of the current. Here, current was switched off for $V_g = +3$ V with $V_a = -1.4$ V and $V_g = -3$ V with $V_a = +1.8$ V, consistent with modeling results that showed changes to the electric field induced by the gate electrode dramatically decrease ionic current when $V_a$ and $V_g$ were of opposite sign.50

 case of a positive axial potential (i.e., $V_a = +3$ V) and a negative gate voltage ($-V_g$), the contribution due to the gate electrode will be opposite to the axial field leading to a decrease in electric field and, therefore, current.

 When the sign of the axial potential is reversed (i.e., $V_a = -3$ V) the relative impact of the gate potential will also be reversed, that is, a $(+V_g)$ decreases the magnitude of the field while a negative gate potential ($-V_g$) increases the magnitude of the field. This leads to a decrease in current (i.e., smaller value of negative current, Figure 5) for $V_a = -3$ V and $V_g > 0$ and an increase in current for $V_a = -3$ V and $V_g < 0$ (i.e., larger value of negative current). In Figure 5, zero current was measured at $V_a = +3$ V, $V_g = -1.4$ V, and $V_g = -3$ V and $V_g = +1.8$ V, consistent with modeling results of Ai et al.50 that showed changes to the electric field induced by the gate electrode dramatically decreased ionic current when $V_a$ and $V_g$ were of opposite sign. In further support of the proposed hypothesis, current modulation in the nanofluidic field effect switch follows the expected dependence on relative axial and gate potential.

 Considering the effect of changing the gate location, as $L_1$ is increased from the center of the channel (0.50 L) toward the grounded microchannel (L), the contribution of the gate electrode to the electric field, $(aV_g/(L - L_1))$, is expected to increase. This means that for a given axial potential $(V_a)$ the change in current induced by the gate electrode will increase as $L_1$ increases. Figure 6 shows measured current at fixed axial voltage for a gate voltage sweep from $-2$ to +2 V for three representative electrode locations of 0.43 L, 0.48 L, and 0.57 L. The current modulation, quantified by the slope $dI/dV_g$ was 0.003 nA/V, 0.014 nA/V, and 0.060 nA/V for 0.43 L, 0.48 L, and 0.57 L respectively. The increased current modulation with $L_1$ indicates increased contribution to the electric field by the gate electrode, as expected.

 Analysis based on electromigration similar to previous reports5,10,42 allows qualitative prediction of observed data trends for various ranges of $V_a$, $V_g$, and $L_1$. However, such an analysis based on electromigration alone does not consider effects of local accumulation and depletion of ions and subsequent changes in species concentrations. As a conce-
tronation gradient in the nanochannel is needed to maintain steady-state current and flux balance for incompressible flow. Detailed modeling or experimental determination of actual ion distributions and analysis of the effect of these gradients on the current in gated nanofluidic channels will be useful and is the subject of future work.

The observed current modulation is expected to depend on bulk KCl concentration.\textsuperscript{6,10} Figure 7 shows a summary of gating effects and analysis of the electric field within the nanochannel. The change in electric field within the nanochannel allows for tunable control of the current through the nanochannels as a function of electrolyte concentration and location of gate electrode. Development of a current switch represents a key addition to existing ionic circuit elements toward the development of fluidic logic circuits.

### ASSOCIATED CONTENT

#### Supporting Information
Measurement of the gate electrode location, gate leakage current, a visual representation of the proposed hypothesis, further details on the experimental methods, and bulk conductance equation. This material is available free of charge via the Internet at http://pubs.acs.org.

#### AUTHOR INFORMATION

**Corresponding Authors**
*E-mail: conlisk.1@osu.edu.*
*E-mail: prakash.31@osu.edu.*

**Author Contributions**

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

**Notes**

The authors declare no competing financial interest.

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**Figure 6.** Current modulation increases as the relative distance of the gate electrode from the channel inlet, \( L_j \), increases, in agreement with the proposed hypothesis. The increase in modulation for the representative case of 1 mM KCl \((V_g = 3 \text{ V})\) is demonstrated by the increase in the slope as shown in the plots above going from the left to right panels.

**Figure 7.** Plot shows dependence of current modulation on bulk KCl concentration for a representative axial potential of \( V_x = 3 \text{ V} \). Error bars were smaller than the markers and are therefore not shown explicitly. Current modulation was observed to decrease as bulk KCl concentration increases likely due to enhanced screening of the gate electrode.

the nanochannels for 0.1 mM to 100 mM KCl at pH 7 ± 0.2. Due to differences in conductance for various concentrations, the current in Figure 7 is reported as a dimensionless current, \( \Delta I/I_0 = (I_{\text{gated}} - I_{\text{ungated}})/I_{\text{ungated}} \). The dimensionless number \( \Delta I/I_0 \) is the change in current due to the gate compared to the current in the ungated case. The current off state (\( I_{\text{gated}} = 0 \text{ nA} \)) corresponds to a dimensionless number of −1. A dimensionless current of 0 indicates the ungated case (\( V_g = 0 \text{ V} \), \( I_{\text{gated}} = I_{\text{ungated}} \)).

Since switching the current off requires \( \Delta I/I_0 = -1 \), as bulk concentration increases higher gate voltage is required to achieve the off current state. The change in current induced by the gate electrode (\( \Delta I \)) is smaller relative to the ungated current (smaller \( \Delta I/I_0 \)) as bulk KCl concentration increases. Decrease in current modulation with increasing bulk KCl concentration is attributed to enhanced screening of the gate electrode by the KCl solution at higher concentrations. At low concentration, a gate voltage of −1.4 V and −3 V was required to switch off the current for 1 mM KCl and 0.1 mM KCl respectively (demonstrated in Figure 3). The lower current modulation for 0.1 mM KCl compared to 1 mM KCl is likely due to increased availability of charge carriers in the 1 mM case as with highly overlapped electric double layers for the 0.1 mM case, the co-ions are excluded from the nanochannels.\textsuperscript{7,53}

A three-state nanofluidic field effect current switch, with a forward current, an off or zero current, and a reverse current state has been demonstrated. For a fixed streamwise potential, the electric field within the nanofluidic channel is altered by systematically controlling the potential applied to a gate electrode embedded within the nanochannel wall. The change in electric field within the nanochannel allows for tunable control of the current through the nanochannels as a function of electrolyte concentration and location of gate electrode.
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**ABBREVIATIONS**

SEM, scanning electron microscope; PDMS, polydimethylsiloxane; DI, deionized; EDL, electric double layer; GLC, gate leakage current

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