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Ion Current Oscillation of Polyelectrolyte Modified Micropipettes

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Abstract: Here, we report for the first time that ion current oscillation (ICO) with periodic amplitude and frequency can autonomously occur at polyimidazole brush (PvimB) modified pipettes in an asymmetric solution with pH gradient (e.g. pH 6.0/pH 8.0). Experimental results demonstrated that under a strong bias voltage, the proton responsible PvimB modified pipettes exhibited significant current switching behavior under negative bias voltages, which contributed to periodic oscillating ion current under constant biases. Based on this dynamic, the frequency and amplitude of the ICO phenomenon were regulated by adjusting the pH gradient in the asymmetric solution. ICO under different bias voltages were further explored to show the voltage-dependent nature of this phenomenon. This observation of ICO phenomena offers a new strategy that designing iontronic devices with dynamic conductivity changes induced by surface chemical interactions in spatial confinements.

Oscillation is the periodic vibration between two or more states, which is widely observed in biological systems (e.g., the circadian clock22 and neural spikes23), chemical systems (e.g., Belousov-Zhabotinsky reaction24), and artificial electronic circuits (e.g., LC oscillation). Oscillations of ion current through the confined nanopores, known as ion current oscillations (ICO), are another type of far-from-equilibrium process that has garnered considerable attention not only for its potential in understanding the behavior of ion channel proteins but also for developing iontronic devices with these phenomena. So far, there are quite limited reports on ICO in nanopore/nanochannels by controlling the gating behavior of nanopore25. For example, Siwy et al. for the first time reported the ICO behavior based on the ion current oscillation between the formation and dissolution or clearance of the nanoprecipitation26. Jiang et al. successfully obtained the ion current oscillation by combination with chemical oscillations27. Moreover, ion current fluctuations and oscillations were also observed at other nanopore system induced by hydrophobic gating28, formation of bubbles29 and the movement of proteins. To the best of our knowledge, no efforts have been made to observe the spontaneous and periodic ICOs by rationally controlling surface chemistry of the inner wall, despite its fundamental interest as well as crucial role in constructing iontronic devices like intelligent neuromorphic devices.

Herein we describe a simple but fundamentally interesting system in which ion current oscillations with spontaneous, continuous and periodic properties are observed. The system is based on a polyimidazole brush (PvimB)-modified micro/nanopipette, which has been developed for ion transport proton sensors that exhibited pH-dependent ion transport behavior due to the protonation/deprotonation of the imidazole groups and the following changes in surface charge. Utilizing surface initiated atomic transfer radical polymerization in a bare micropipette fabricated by laser puller, PvimB modified micro/nanopipettes were fabricated as reported (Figure 1A and Supporting information S1). By backfilling and immersing the micro/nanopipettes with phosphate buffered saline (PBS) of different pH, oscillating ion current could be observed under intensive negative bias voltages (Figure 1B). Furthermore, by controlling the pH gradient and applied bias voltage in spatial confinement, frequency and amplitude of the ICO could be manipulated by regulating the conductivity switch dynamics in the spatial...
confinement through tuning the applied bias and pH gradient. This observation offers a new strategy for manipulating the confined ion transport behaviors with the changes on surface chemistry autonomously and provided novel perspective for the design of iontronic devices.

To ensure the successful fabrication of the PvimB modified micropipettes, the I-V curves of the PvimB modified micropipettes in PBS at different pH level showed that the PvimB modified micropipette shows typical ICR and memristive effects under triangular waves in a pH 5.8 acidic environment, while demonstrates almost ohmic response in a pH 8.0 alkaline environment. These results confirm that the pH responsible PvimB was successfully modified onto the inner surface of the micropipettes, thereby enabling the conductivity of the micropipette to be easily regulated by pH change in the micropipette under negative biases.

In the ICO investigation reported here, the PvimB-modified micropipette was inserted into an alkaline PBS solution (pH 8.0), while the inner solution was backfilled with an acidic PBS solution (pH 6.0), as shown in Figure 1B. When an intensive negative bias (e.g., $E_{\text{external}} - E_{\text{internal}} = -10\,\text{V}$) was applied to a 3-μm-diameter PvimB-modified micropipette, typical oscillating ion current was observed with periodic and continuous characteristics (Figure 2, red curve).

In contrast, no oscillating ion current could be observed without the pH gradient, and the micropipette showed a typical accumulating high conductivity state in pH 8.0 alkaline solution (Figure 2, blue curve) and a depleting low conductivity in pH 6.0 acidic environment (Figure 2, green curve). Furthermore, the oscillating ion current in asymmetric solution vibrates between the pH 6.0 low conductive state and the pH 8.0 high conductive state. This observation indicated that the ICO observed herein is related to the conductivity switch between the protonated low conductivity state and the deprotonated high conductivity state.

Based on this understanding, pH gradient within the modified micropipette was first regulated to show the impact of ion distribution as predicted. As depicted in Figure 3, the modified micropipettes were able to show significant ICO behavior even under a small pH gradient (pH 7.4/pH 6.0) (Fig. 3C), demonstrating that a minimal conductivity difference within the system is sufficient to induce the ICO effect. With the raise of pH gradient, current difference between the high conductivity state and the low conductivity state, i.e. ICO amplitude, was regulated owing to the reduced difference between high conductive deprotonated state and low conductive protonated state. Figure 3A-C showed that under -10 V bias voltages (Figure 3A, E), the PvimB modified micropipette showed 11.55 nA amplitude in a weak pH gradient (pH 7.4/pH 6.0) (Figure 3C), while behaved 0.11 μA amplitude in pH gradient (pH 8.0/pH 6.0) (Figure 3B) and showed a 4.53 μA intensive amplitude in a strong pH gradient (pH 9.0/pH 5.0) (Figure 3A). The conductivity difference under different pH contributed to the occurrence of ICO, therefore the raise of pH gradient contributed to the changes on the conductivity difference between the high conductivity state and the low conductivity state. In this case a significant enhancement of amplitude could be observed with the raise of pH gradient.

To theoretically understand the conductivity switch dynamics of the ICO phenomena, the current change was further evaluated by calculating the resistance distribution in each part (Supporting Information 2). For a modified micropipette in asymmetric solution, the resistance of the micropipette could be simplified as 3 sections, bulk solution resistance $R_{\text{bulk}}$, protonated section surface resistance $R_{\text{surface, A}}$, and deprotonated surface resistance $R_{\text{surface, B}}$. The current through the micropipette could be calculated according to the geometry of the modified micropipette according to Ohm’s law. It was shown that the current through the modified micropipette is related to the ion distribution, applied bias voltage and the changes of protonation (deprotonation) section. When a negative bias was applied to the modified micropipette, changes in proton distribution under electrical field contributed to periodic conductivity changes and following occurrence of ICO.
Additionally, as the pH gradient increased, a notable decrease of ICO frequency could be observed in the modified micropipette. Power spectral analysis of the I-t curves under -10 V bias (Figure 3D) revealed a significant red shift of the power spectra peak with the escalation of pH gradient, which is coincident with the accelerated ICO behavior observed in the I-t curves under -10 V. Under a weak pH gradient (pH 7.4/pH 6.0), the modified micropipette showed a faster oscillating frequency of 0.87 Hz under constant bias; and the ICO frequency reduced to 0.30 Hz in a gradient pH (8.0/pH 6.0) and 0.16 Hz in a pH gradient (9.0/pH 5.0). The increased discrepancy between the high conductivity state and the low conductivity influenced the transition time between the two states, resulting in a lower frequency observed in the ICO phenomena. This ICO observation herein is contingent upon the surface chemical interactions, as a result a simple pH alternation could effectively regulate the kinetics of the oscillating behavior, presenting an opportunity of establishing a universal approach for oscillating nanconfinements with deliberate surface chemistry design.

Apart from the pH gradient impact, the influence of applied bias voltage on ICO phenomena was further investigated to show the voltage response of the fundamental voltage response of the device. I-t curves of a PvimB modified micropipette in pH 8.0/pH 6.0 asymmetric solution under various bias voltages showed that a noticeable decrease in frequency apart from the significant amplitude changes could be observed when bias voltage decreased from -8 V to -5 V (Figure 4A-C). This frequency reduction is also evident in the red shift of the power spectra peaks under different bias voltages (Figure 4D), indicating a decrease in oscillating frequency from 51 mHz to 33 mHz when reducing the applied bias voltage from -8 V to -5 V. Alteration in the bias voltages directly contributed to the reducing electroosmotic flow and electrophoresis in spatial confinement. Consequently, the conductivity switch dynamic could be manipulated by the voltage changes, leading to the voltage dependent ICO observation herein.

![Figure 4](image-url) **Figure 4** (A-C) I-t curves of a PvimB modified micropipette in PBS pH 8.0/PBS pH 6.0 asymmetric solution under different biases: (A) -10 V, (B) -7 V, (C) -5 V; (D) Power spectra derived from (A-C): Plots of frequency of the ICO phenomena under different biases.

In conclusion, an ICO phenomenon was observed in PvimB modified micropipette under intensive bias voltages. Originating from periodic surface conductivity switch between the deprotonation state and protonation state in asymmetric solution under negative bias voltage, ICO could be spontaneously achieved in self-gating mode. This observation presents a novel strategy for fabricating periodic ion transport devices with the switch of intrinsic conductivity states of nanconfinements in different environments. Notably, the observed ICO is manipulated by changes of surface chemistry in spatial confinement, offering promising versatility to this phenomenon. With the assistance of rational surface functionalization, ICO triggered by chemicals could be designed and fabricated. In this case not only ICO-based sensing techniques but also novel ionotronic devices with nonlinear conductivity dynamic triggered by transmitters could be achieved with this ICO dynamic.

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**Conflicts of Interest**

There are no conflicts to declare.

**Notes and references**

Data Availability Statement

The authors declare that the data that support the findings of this study are available within the paper and its supplementary information files. Additional data and files are available from the corresponding author upon reasonable request.