Electrochemistry Communications 93 (2018) 95–99

Contents lists available at ScienceDirect

Electrochemistry Communications

journal homepage: www.elsevier.com/locate/elecom

Ion-current-rectification-based customizable pH response in glass nanopipettes via silanization

Guo-Chang Liu[a], Wei Chen[a,*], Meng-Juan Gao[a], Lai-Bo Song[a], Xiao-Yu Hu[a,b], Yuan-Di Zhao[a,c]

[a] Britton Chance Center for Biomedical Photonics at Wuhan National Laboratory for Optoelectronics-Hubei Bioinformatics & Molecular Imaging Key Laboratory, Department of Biomedical Engineering, College of Life Science and Technology, Huazhong University of Science and Technology, Wuhan 430074, PR China
[b] Hubei Boffin Technology Co. Ltd., Wuhan 430074, PR China
[c] Key Laboratory of Biomedical Photonics (HUST), Ministry of Education, Huazhong University of Science and Technology, Wuhan 430074, PR China

ARTICLE INFO

Keywords:
Nanopipette
Ion current rectification
Customizable pH response
Silanization

ABSTRACT

This study shows that it is possible to customize the ion-current-rectification (ICR)-based pH response in glass nanopipettes by adjusting the ratio of 3-aminopropyldimethylethoxysilane (APTES) and (3-triethoxysilylpropyl) succinic acid anhydride (TESP-SA) used in silanization. The silanization time and concentration were optimized by investigating the rectification ratio of the nanopipettes. For each APTES/TESP-SA silane ratio, analysis of variance (ANOVA) tests indicated that the rectification ratio of the nanopipette had good linearity in the pH range 3–8. Moreover, nanopipettes silanized with equal concentrations of amino and carboxylic groups gave the highest pH response of $1.06 \times 10^{-4}\,\mathrm{pH}^{-1}$. This method for customizing the ICR-based pH response in nanopipettes has the potential and versatility to be used in applications such as mimicking biological ion channels and developing nanosized pH sensing devices.

1. Introduction

Since the discovery of nonlinear ion current–voltage behavior in a quartz nanopipette [1], the phenomenon of ion current rectification (ICR) has attracted much attention and has been observed in silica nanochannels [2, 3], quartz nanopipettes [4, 5], nanopores in poly(ethylene terephthalate) film [6–9] and nanopores in polyimide film [10]. Based on this observation, nanopore structures have been utilized to construct biomimetic ion channels [11, 12], biosensors [13, 14], ion permselective membranes [15] and ion pumps [16]. In these applications, the surface functionalization of the nanopores needs to be carefully planned and implemented by means of either physical adsorption [17, 18] or chemical modification [19, 20] using various functional groups.

In biological ion channels, ICR is mainly caused by the presence of specific charges of amino acid residues at the intracellular end of the pore [21–23]. Inspired by these biological examples, the construction of artificial nanochannels that are responsive to pH has become an exciting target for researchers since pH is significant in many physical and chemical processes. The precise functionalization of the inner pore walls with pH-sensitive molecules is essential in obtaining an ICR-based pH response, since the rectification properties of conical nanopores rely mainly on their inner surface charge [24]. Various molecules with functional groups such as poly(2-(methacryloyloxy)ethyl phosphate), 6-carboxymethyl-chitosan and chitosan have been employed to construct pH-sensitive nanopores [18–20]. Though each molecular functionalization produces a specific pH response behavior in the nanopore, it is difficult to design and synthesize a versatile molecule which demonstrates pH-responsive rectification behavior over a wide pH range. It is therefore important to develop a universal functionalization strategy that allows the ICR-based pH response to be easily customized.

In this study, we develop a direct, simple and effective method that customizes nanopipette pH response by adjusting the ratio of amino silane and anhydride silane in the pre-silanization solution. The functionalization conditions, including silanization time and silane concentration, are optimized. Nanopipettes with various amino/anhydride silane ratios are fabricated and their rectification responses over a range of pH values (3 to 8) are investigated.

2. Experimental

2.1. Materials and apparatus

Citric acid, 3-aminopropyldimethylethoxysilane (APTES) and (3-triethoxysilylpropyl) succinic acid anhydride (TESP-SA) were purchased from J&K Scientific Ltd. Potassium chloride and dipotassium

---

[*] Corresponding author.
E-mail address: chen1980wei@hust.edu.cn (W. Chen).

https://doi.org/10.1016/j.elecom.2018.06.015
Received 11 June 2018; Received in revised form 28 June 2018; Accepted 28 June 2018

hydrogen phosphate trihydrate were obtained from Sinopharm. Phosphate/citrate buffers with pH values of 2.24, 3.00, 4.00, 5.05, 6.02, 7.02 and 8.00 were prepared by varying the ratio of sodium phosphate dibasic and citrate, respectively. All the solutions used for the electrochemical characterizations contained 20 mM phosphate/citrate buffer and 0.1 M potassium chloride and were prepared with deionized water (18 MΩ·cm, Millipore). Borosilicate capillaries with 1.5 mm external diameter and 0.75 mm internal diameter were purchased from World Precision Instrument Inc. SEM images of the nanopipettes were taken by a Helios G3CX FESEM (FEI) with an accelerating voltage of 5 kV without Au sputter coating. The pH of the solution was determined using a FE20/EL20 laboratory pH meter (METTLER TOLEDO). Linear sweep voltammetry was performed on a CHI 830D electrochemical workstation (CH Instrument Co. Ltd., Shanghai). The nanopipettes were fabricated on a P-2000 laser puller (Sutter Instruments Co.).

2.2. *Nanopipette preparation*

Borosilicate capillaries were cleaned with freshly prepared Piranha solution for 0.5 h at room temperature, and then thoroughly rinsed with pure water. After being dried at 80 °C, the capillaries were pulled to a diameter of around 90 nm with following settings: Heat = 325, Fil = 0, Vel = 10, Del = 145, Pull = 180. The resulting nanopipettes were examined using SEM. As shown in Fig. 1(a) and (b), the cone angle and diameter of the nanopipette tip are estimated as 8.3° and ~90 nm, respectively. The measured tip diameter is also in accordance with the results calculated from the electrochemical measurement [25]. A schematic diagram of the nanopipette functionalization and working principle is shown in Fig. 1(c). The nanopipettes were functionalized by backfilling APTES and TESP-SA ethanol solutions of various concentrations and in different ratios for certain incubation times at room temperature. After silanization, the nanopipettes were thoroughly rinsed with 95% ethanol to remove unreacted silanes, and then oven-dried at 110 °C for 0.5 h. The functionalized nanopipettes were filled with 0.1 M potassium chloride using a microsyringe and were then ready for use.

2.3. *Electrochemical characterization*

Two Ag/AgCl wires 0.5 mm in diameter were placed in the nanopipette and bulk solution, respectively. The ion current measurements were recorded in a potential range from −1 V to +1 V at a scan rate of 0.1 V/s. The nanopipettes were thoroughly rinsed with 0.1 M KCl after each measurement. The responses of the nanopipettes at various pHs were recorded in a series of 0.1 M KCl solutions with pH values of 2.24, 3.00, 4.00, 5.05, 6.02, 7.02 and 8.00. The rectification ratio r ($r = \log_2 |I_+/I_-|$, where I_+ and I_- refer to the ion current at the bias voltage of +1 V and −1 V, respectively) was used to represent the rectification status of the nanopipettes. When $r > 0$, the nanopipette is anion-selective and the inner surface charge of the nanopipette is positive. When $r < 0$ the nanopipette is cation-selective and the inner surface charge of the nanopipette is negative.

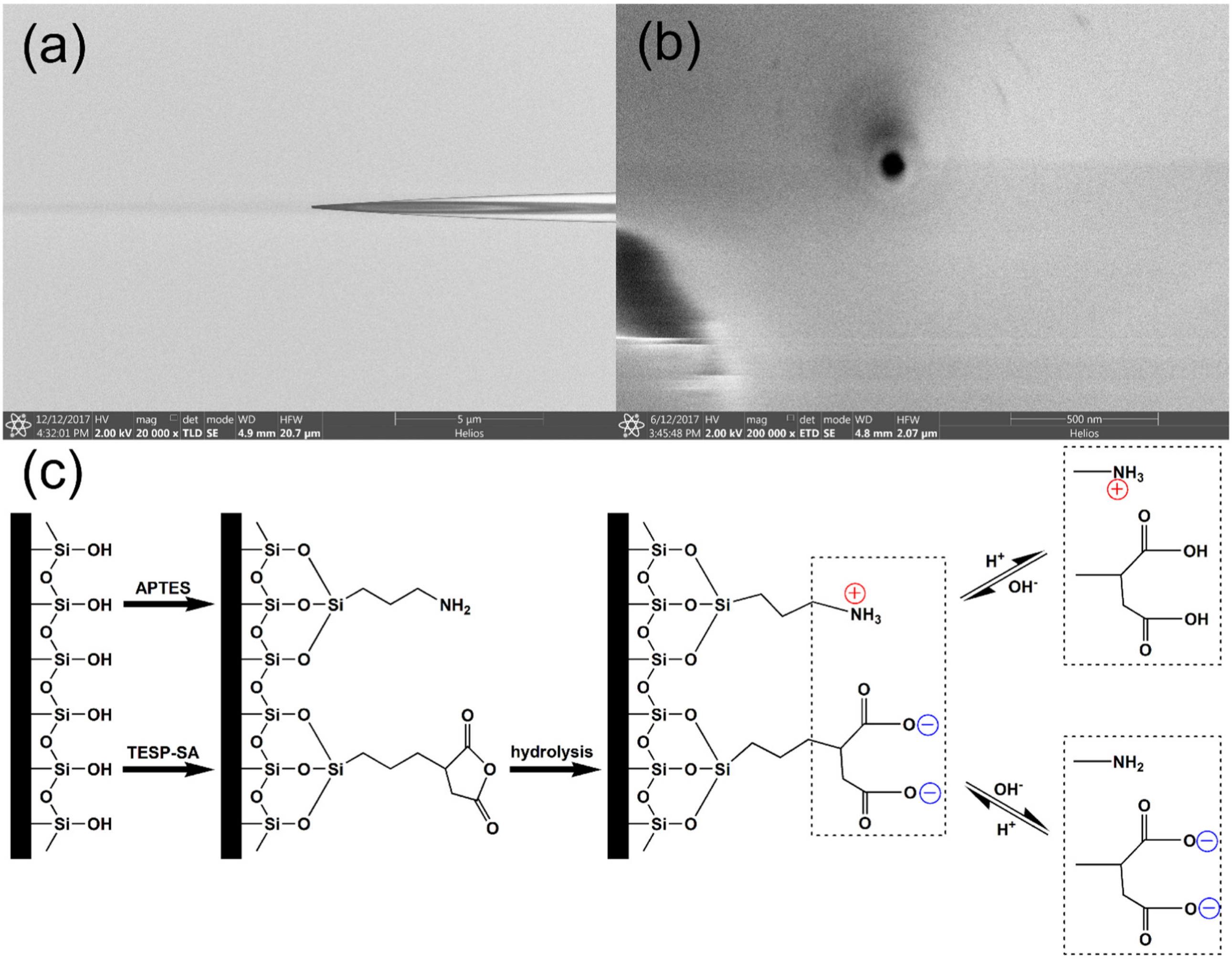

Fig. 1. SEM images of the nanopipettes: (a) side view; (b) end-on view. (c) Schematic diagram showing nanopipette functionalization and working principle.