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Hodgkin–Huxley Artificial Synaptic Membrane Based on Protonic/Electronic Hybrid Neuromorphic Transistors

Yang Ming Fu[†], Dr. Chang Jin Wan[†], Prof. Li Qiang Zhu^{*}, Hui Xiao, Prof. Xiao Dong Chen^{*}, Prof. Qing Wan^{*}

Yang Ming Fu, Prof. Li Qiang Zhu, Hui Xiao

Key Laboratory of Graphene Technologies and Applications of Zhejiang Province, Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences, Ningbo 315201, Zhejiang, People's Republic of China and University of Chinese Academy of Sciences, Beijing 100049, Peoples Republic of China

E-mail: lqzhu@nimte.ac.cn

Dr. Chang Jin Wan, Prof. Xiao Dong Chen

School of Materials Science and Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

E-mail: chenxd@ntu.edu.sg

Prof. Qing Wan

School of Electronic Science & Engineering, Nanjing University, Nanjing 210093, Jiangsu, Peoples Republic of China

E-mail address: wanqing@nju.edu.cn

[[†]] These authors equally contributed to this article.

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Abstract: Iontronics is a newly emerging interdisciplinary concept that bridges electronics and ionics. It provides new opportunities for biomimic information processing. Iontronic devices can act as building blocks for neuromorphic platforms. Here, proof-of-principle Hodgkin–Huxley artificial synaptic membrane is proposed for the first time based on inorganic proton conductor. PSG-based proton conductor electrolyte demonstrates unique short-term volatile charging behaviors, indicating potential short-term synaptic plasticity applications. By using protonic/electronic hybrid oxide transistor configuration, dynamic synaptic membrane potential responses are triggered with gate current spikes. Typical resting potential, excitatory/inhibitory post-synaptic potential behaviors and membrane depolarization/activation behaviors are mimicked on the proposed Hodgkin–Huxley artificial synaptic membrane. Moreover, proton related electrostatic coupling enables the device to possess short-term synaptic plasticities with low power consumption. The proposed Hodgkin–Huxley artificial synaptic membrane provides a new prototype for neuromorphic system applications.

Iontronics is a newly emerging interdisciplinary concept that bridges electronics and ionics, covering electrochemistry, solid-state physics, electronic engineering and biological science [1]. Iontronic devices offer profound implications for biocompatible or biodegradable logic circuits for sensing, ecofriendly monitoring, and brain-machine interfacing [2]. In recent advancements of condensed matters, ions are endowed with new intension. Phase transformations of condensed materials from one state to others are observed by using electric field to control ion migration and ion doping, which greatly enrich material functionality [3, 4]. Our brain has $\sim 10^{11}$ neurons and $\sim 10^{15}$ synapses [5]. Ions activities also play a vital role in nervous responses in biological systems [6, 7]. Ion fluxes in neurons and synapses involve physical alterations in neural substrates, modulating neuron activities and communications.

Such architecture makes our brain possess a significant computational ability, underling all the human brain functions, including perception, learning, memory, etc [8, 9]. Interestingly, the energy consumption for brain computation is only ~20W [10].

Inspired by such high efficient network of our brain, neuromorphic engineering has attracted world-wide attention. Conventionally, von Neumann Architecture has been proposed for establishing neuromorphic systems [11]. However, a control unit, an arithmetic logic unit and a memory are physically separated. Such configuration is becoming increasingly inefficient when meeting complicated real-time computation [12]. Thus, brain-inspired neuromorphic computation beyond von Neumann Architecture is needed. Iontronics provides new opportunities for biomimic information processing [2]. Iontronic devices can act as building blocks for neuromorphic platforms. Mixed ionic-electronic conductor based memristors and atomic switches are typical iontronic devices and have recently been proposed for neuromorphic systems applications [13-18]. Synaptic plasticities, pattern recognition and sparse coding were realized, indicating great potentials for these artificial synapses [19, 20]. As typical iontronic devices, ionic liquid or ionic gel based electrolyte gated transistors (EGTs) can be ideal candidates for artificial synapse/neuron applications due to the unique ionic/electronic coupling behaviors, demonstrating several synaptic functions [3, 21-30].

A biological synapse is composed of pre-synaptic membrane, synaptic cleft and post-synaptic membrane, as schematically shown in **Figure 1a**. The synaptic membrane serves as both an insulator and a diffusion barrier for ions. Membrane potential, resulting from ionic concentration difference between the intracellular and extracellular membrane, is crucial for signal transmission [31]. This potential value is generally held at a relatively stable resting voltage ranged between -40 mV and -80 mV [32, 33]. It can also be dynamically polarized or depolarized by ion transport across membranes. Once the membrane potential is depolarized or even anti-polarized to a certain threshold value, an action potential can be ignited. This all-

or-nothing spiking is a central point for understanding computational capability of nerve system and emulating its functionality [34-37]. In membrane biophysics, Hodgkin-Huxley model is proposed for understanding computational capability of nervous system and emulating its functionality in terms of action potential generation in biological axons [38, 39]. Figure 1b shows a simplified equivalent circuit used in Hodgkin–Huxley model for a bio-membrane. Each component of an excitatory neuron cell can be deemed as an electrical element. A synaptic membrane is composed of a lipid bilayer with proteins embedded in it. The lipid bilayer is represented as a capacitance (C_{Lipid}). Ion transporter/pump proteins actively push ions across the membrane and establish concentration gradients across the membrane. Such ion pumps and ion channels can be electrically equivalent to a set of batteries (E_n) and resistors (G_n) inserted in the membrane. The ion pumps and exchangers are represented by current sources. Previously, a neuristor was built by HP Labs using a pair of nanoscale Mott memristors [40]. The neuristor has similar properties to the Hodgkin-Huxley axon, exhibiting important neural functions of all-or-nothing spiking. With unique ionic/electronic coupling, ionic liquid or ionic gel electrolyte can find potential applications in mimicking synaptic membrane potential responses. In this communications, we provide, for the first time, proof-of-principle Hodgkin-Huxley artificial synaptic membrane based on inorganic proton conductor in a transistor configuration, as shown in Figure 1c. An additional in-plane modulatory terminal is introduced for an in-plane gate indium tungsten oxide (IWO) transistor operating in self-modulation mode. Figure 1d shows the simplified equivalent circuit which is similar to the resistor-capacitor (RC) circuit used in Hodgkin–Huxley model. Dynamic synaptic membrane potential responses were observed. Typical resting potential, excitatory/inhibitory post-synaptic potential behaviors and membrane depolarization/activation behaviors were mimicked. The devices possess short-term synaptic

plasticities with low power consumption. The proposed artificial synaptic membrane provides a new prototype for neuromorphic applications.

Figure 1. (a) Simplified illustration of a biological synapse. (b) Simplified equivalent circuit used in Hodgkin–Huxley model. C_{Lipid} represents the capacitance of lipid bilayer. E_n and G_n represent the batteries and resistors of ion pumps and ion channels in membrane. (c) Proposed artificial synaptic membrane based on inorganic proton conductor in a transistor configuration. G, D, S and G_m represent in-plane gate, drain, source and modulatory terminal, respectively. V_{G_m} is the bias applied on G_m . (d) Simplified equivalent circuit of the artificial synaptic membrane.

Figure 2. (a) Cross-sectional scanning electron microscope (SEM) image of phosphosilicate glass (PSG)-based electrolyte film deposited on Si substrate. Inset: Transmission electron microscopy (TEM) image of the PSG electrolyte film. (b) Leakage current for PSG-based electrolyte. Inset: In-plane IWO/PSG/IWO capacitor. (c) Potential responses of thermally grown SiO₂ and PSG electrolyte based capacitors as a function of time upon current spikes. (d) Extracted peak voltage potential (V_{peak}) at the end of each current spike. The V_{peak} value has been offset from the previous stimulus, i.e., $V_{\text{peak}} = V_{\text{peak}}^n - V_{\text{peak}}^{n-1}$.

Inset in **Figure 2b** illustrates a schematic diagram of an in-plane IWO/PSG/IWO capacitor. An IWO/SiO₂/P⁺⁺-Si capacitor is also obtained acting as a controlled sample. Thermally grown SiO₂/P⁺⁺-Si is commercially available. The detailed descriptions are presented in Experimental Section. Figure 2a shows cross-sectional SEM image of PSG

electrolyte film. Inset in Figure 2a shows TEM image of PSG electrolyte film. The results indicate that the solid-state electrolyte film is composed of PSG grains with size of $\sim 10\text{nm}$. While it is dense for commercially obtained thermally grown SiO_2 film. Figure 2b shows leakage current of PSG based electrolyte. The leakage current is less than 2nA at voltage bias ranged between -2V and 2V . While the leakage current for thermally grown SiO_2 is only $\sim 5\text{pA}$ at the same voltage bias range, as shown in Figure S2. Furthermore, charging behaviors of PSG based electrolyte and thermally grown SiO_2 films were studied. **One electrode is biased with current spikes and another electrode is grounded. Intrinsic potential responses of the MIM capacitor can be measured on the electrode.** Figure 2c illustrates potential responses as a function of time. The spike amplitude increases from 10nA to 60nA with a constant spike duration time of 7ms . No volatile behavior is observed after charging process for thermally grown SiO_2 . There is no decay in the induced potential when the applied current spike ends. However, the situation is quite different for PSG electrolyte. A short-term decay is observed in the induced potential when the applied current spike ends, exhibiting volatile behavior. Figure 2d shows the extracted peak voltage potential (V_{peak}) at the end of each current spikes. For thermally grown SiO_2 , V_{peak} increases from $\sim 130\text{mV}$ to $\sim 750\text{mV}$ for current spike amplitude increases from 10nA to 60nA . While for PSG electrolyte, V_{peak} increases from $\sim 30\text{mV}$ to $\sim 130\text{mV}$ with spike amplitude increases from 10nA to 60nA . In terms of capacitor using PSG electrolyte as dielectric, a certain amount of electrons will accumulate at the electrode after applying a current spike. Moreover, an interfacial electric-double-layer (EDL) layer will form at the PSG/electrode interface. When the spike ends, the accumulated electrons will leak away and the accumulated protons will migrate back to equilibrium position too, which results in a decayed potential. The observations indicate potential short-term plasticity behavior applications [41]. Moreover, there is a slight increase in the resting potential, indicating potential long-term plasticity behavior applications.

PSG electrolyte could be deemed as a RC circuit consisting of a resistor (R) in parallel with a capacitor (C), as shown in **Figure 3a**. Thus, we have relation below:

$$I(t) = \frac{U(t)}{R} + C \cdot U'(t) \quad (1)$$

where $I(t)$ and $U(t)$ are the applied current spike and the triggered potential across the PSG electrolyte based capacitor. The detail analysis can be found in Supplementary Information (SI-5). When there is no current biased on the electrolyte, there will be no charging behavior. Thus, $U(t)$ is zero. While when a current spike is applied on the electrolyte, charging process occurs. Figure 3b schematically shows current spike which can be written with a relation below:

$$I(t) = H \cdot [Heaviside(t - T_1) - Heaviside(t - T_2)] \quad (2)$$

where H , T_1 and T_2 are the spike amplitude, the spike starting time and the spike finishing time, respectively. Figure 3c shows potential responses as a function of time upon positive or negative current spikes. For positive current spike of (20nA, 14ms), a peak potential of ~145mV is obtained. While for negative current spike of (-20nA, 14ms), a peak potential of ~-145mV is obtained. Potential responses upon current spikes can be fitted by equation (1) and equation (2). As shown in Figure 3c, the fitted curves approach the measured curves very well. In neuroscience, paired-pulse facilitation (PPF) is an essential form of short-term synaptic plasticity where the second post-synaptic response is stronger than the first one.[42] Such PPF behavior can be mimicked on the PSG based capacitor. Inset in Figure 3d illustrates a typical post-synaptic potential (PSP) response upon two successive positive current spikes (20nA, 14ms) with an interval time of ~350ms. The second peak (A_2) is obviously larger than the first one (A_1). A_2 and A_1 are estimated to be ~186mV and ~145mV, respectively. Thus, PPF Index, defined as $100\% \times A_2/A_1$, is estimated to be ~128%. Figure 3d systematically shows that PPF Index decreases with the increased interval time. It decreases from ~160% to ~110% with the interval time increases from ~20ms to ~1.4s. **It should be noted here that**

different behaviors will be observed when applying voltage spikes. Figure 3e shows a typical current response upon a voltage spike of (0.1V, 20ms) applied on the IWO/PSG/IWO capacitor. The resting current is zero due to the zero bias. When the spike arrives, a peak current value of $\sim 18\text{nA}$ is detected. When the spike ends, a negative current value of $\sim -14\text{nA}$ is detected. Then, the current value gradually decays back to zero. This behavior is attributed to charging and discharging effects of the PSG based capacitor along with the slow proton migration within the PSG electrolyte.

Figure 3. (a) Schematic diagram for PSG electrolyte based in-plane IWO/PSG/IWO capacitor. The PSG electrolyte can be deemed as a resistor (R)-capacitor (C) circuit. (b) Schematic diagram of the applied current spike. H , T_1 and T_2 are the spike amplitude, the spike starting time and the spike finishing time, respectively. (c) Potential responses of PSG electrolyte based capacitor upon positive or negative current spikes. (d) Paired-pulse facilitation (PPF)

Index plotted as a function of interval time. Inset: a typical post-synaptic potential (PSP) stimulated with two successive positive current spikes (20nA, 14ms) with an interval time of ~350ms. A_1 and A_2 are amplitudes of the first and second PSPs. PPF Index is defined as $100\% \times A_2/A_1$. (e) A typical current response upon a voltage spike of (0.1V, 20ms) applied on the IWO/PSG/IWO capacitor.

Another notable feature of the PSG electrolyte is its high proton conductivity and high EDL capacitance. SI-3 discusses capacitance and impedance characteristics of the nanogranular PSG electrolyte film. A high proton conductivity of $\sim 8.7 \times 10^{-4} \text{ S cm}^{-1}$ and a high EDL capacitance of $\sim 3.5 \mu\text{F cm}^{-2}$ were obtained for the PSG electrolyte. **Figure 4a** illustrates fifteen repeated transfer curves of the IWO EDL neuromorphic transistor. The transfer curves approach with each other very well, indicating good stabilities of the fabricated transistors. Previously, ionic liquid (IL) electrolyte gated SmNiO_3 transistor is proposed. [43] With the IL gating, electrochemical reactions at the IL– SmNiO_3 interface is observed. Due to the creation and annihilation of oxygen vacancies, the conductivity of SmNiO_3 channel can be modulated. Moreover, proton gated phase-change transistor has also been reported, where proton doping results in a sharp phase transition in SmNiO_3 . [44] In our case, EDL effects result in the modulation of channel conductivity. When the in-plane gate is biased at positive voltage, protons within the PSG electrolyte will accumulate at the PSG/channel interface. Due to the formation of EDL layer at the PSG/channel interface, a high channel current is observed. When the in-plane gate is biased at negative voltage, the IWO channel will get depleted, resulting in a decreased channel current. Furthermore, current spike triggered drain potential responses were discussed for the IWO transistor worked in self-modulation mode with gate short-connected to drain. Current spike is applied on the gate. Figure 4b schematically

illustrates the working mechanism of the transistor worked in self-modulation mode. Figure 4c illustrates a simplified equivalent circuit correspondingly. Thus, we have a relation below:

$$I(t) = \frac{\mu W}{2L} C_G \cdot U(t)^2 + \left[\frac{1}{R} - \frac{\mu W}{2L} C_G \cdot V_T \right] \cdot U(t) + C_G \cdot U'(t) \quad (3)$$

where μ , W , L , C_G and V_T are mobility, channel width, channel length, gate capacitance and threshold voltage, respectively. The detail analysis can be found in Supplementary Information (SI-5). Figure 4d illustrates drain potential responses upon positive or negative current spikes. When a positive current spike (20nA, 14ms) is applied on the gate, V_{peak} of $\sim 100\text{mV}$ is observed on the drain followed by a gradual decay. While when a negative current spike (-20nA, 14ms) is applied on the gate, V_{peak} of $\sim -80\text{mV}$ is observed on the drain followed by a gradual decay. Such behaviors are similar to excitatory postsynaptic potential (EPSP) and inhibitory postsynaptic potential (IPSP) responses observed in neural system [32, 33]. When a negative current spike is applied on the gate, a current will flow in the channel, which produces a negative potential on the drain. Moreover, the electrolyte is charged with protons accumulated at electrolyte/gate interface, forming an EDL layer there. When the current spike ends, protons will migrate back to their equivalent position. Therefore, electrons accumulated at the gate will migrate to the ground through channel. Thus, a decayed potential is observed. The potential response upon current spike can also be fitted from equation (2) and equation (3). As shown in Figure 4d, the fitted curves approach the measured curves very well.

Figure 4. (a) Typical transfer curves measured for 15 times at a constant V_{ds} of 1.5V. Inset: Schematic diagram of the IWO transistor. The bottom ITO conductive layer is floated. The bias on the in-plane gate will couple to bottom ITO layer and then couple to the IWO channel. (b) Schematic diagram of working mechanism of IWO neuromorphic transistor. (c) Simplified equivalent circuit. (d) Potential responses of the IWO transistor upon positive or negative current spikes.

A synapse is composed of pre-synaptic membrane, synaptic cleft and post-membrane, as schematically shown in Figure 1a. When active pre-synapse releases neurotransmitters into synaptic cleft, some of them would bind to receptors on post-synapse. Thus, receptors containing ion channels can let ions pass, which results in depolarizing, repolarizing or hyperpolarizing the membrane [45, 46]. For excitatory synapses, ion channel typically allows sodium transfer into neuron cell, generating an excitatory postsynaptic current (EPSC). This depolarizing current enhances interior membrane potential, triggering EPSP. For inhibitory synapse, sodium ions flow out of neuron cell, triggering a hyperpolarizing current, which makes interior membrane potential more negative, triggering IPSP [32, 33]. In excitatory neuron cells, a sufficiently large depolarization can evoke an action potential. For the as fabricated oxide EDL transistor, the observed potential responses hint its potential applications in artificial synaptic membrane. Figure 1c shows proof-of-principle Hodgkin–

Huxley artificial synaptic membrane based on inorganic proton conductor in a transistor configuration. Due to synergic proton coupling behaviors, an additional in-plane modulatory gate can effectively change channel conductivities (shown in Figure S4b). Figure 1d shows the simplified equivalent circuit. Thus, we have the relation below:

$$I(t) = \frac{\mu W}{2L} C_G \cdot U(t)^2 + \left[\frac{1}{R_1} - \frac{\mu W}{2L} C_G \cdot V_T \right] \cdot U(t) + C_1 \cdot U'(t) - \frac{V_{Gm}}{R_1} \quad (4)$$

where V_{Gm} is the bias applied on the modulatory terminal. The detail analysis can be found in Supplementary Information (SI-5). To mimic synaptic membrane potential responses, we have applied current spike on the gate and applied a constant negative bias (V_{Gm}) on the modulatory terminal. Thus, a membrane potential response can be detected on the drain.

Figure 5a illustrates the membrane potential responses triggered by current spikes applied on the gate. The modulatory terminal is biased at -70mV. A resting drain potential of ~-60mV is obtained, which is quite similar to a typical resting membrane potential ranged between -40mV and -80mV in nerve system [32, 33]. When a positive current spike (20nA, 14ms) is applied on the gate, a positive shift in drain potential is observed. While when a negative current spike (-20nA, 14ms) is applied on the gate, a negative shift in drain potential is observed. Such behaviors are quite similar to EPSP and IPSP responses in post-synaptic membrane, respectively [32, 33]. Figure 5b schematically illustrates operating mechanisms. When a negative bias is applied on the modulatory terminal, a small channel current (noted as i_1) flows from source to drain due to a small leakage current on G_m . Thus, a negative potential is observed on the drain, which corresponds to negative resting membrane potential. When applying positive current spike, current flowing from drain to source (noted as i_2) will compensate current i_1 . When i_1 is higher than i_2 , effective channel current will flow from source to drain, which results in a negative potential on the drain. While when i_1 is lower than i_2 , effective channel current will flow from drain to source. Thus, a positive drain potential will be observed. As shown in Figure 5a, a peak potential value of ~0mV is obtained at the

end of positive current spike of (20nA, 14ms), followed by a gradual decay in potential back to a resting value of $\sim -60\text{mV}$ in $\sim 2\text{s}$. The behavior is similar to an EPSP response in nerve system [47]. While a peak potential value of $\sim -120\text{mV}$ is obtained at the end of negative current spike of (-20nA, 14ms), followed by a gradual decay in the potential back to a resting value of $\sim -60\text{mV}$ in $\sim 2\text{s}$. The behavior is similar to an IPSP response in nerve system [48]. The potential response upon current spike can also be fitted from equation (2) and equation (4). As shown in Figure 5a, the fitted curves approach the measured data very well.

Figure 5. (a) Potential responses of the proposed artificial synaptic membrane upon current spikes (20/-20nA, 14ms). The fitted curves approach the measured data very well. (b) Schematic diagram of the operating mechanisms. (c) Peak post-synaptic potential (PSP) value as a function of current spike duration time at different spike amplitude. (d) and (e) EPSP curves triggered with one and three current spikes, respectively. One single EPSP does not

sufficiently depolarize the membrane. Summation of three EPSPs depolarizes the membrane to generate an action potential.

It should be noted here that the polarity of the membrane potential of the artificial synaptic membrane is also depended on charging behavior of the PSG electrolyte. With the increased positive current spike duration time, the membrane potential will shift from negative to positive. Figure 5c shows peak post-synaptic potential (PSP) value as a function of current spike duration time at different spike amplitude. For spike amplitude of 5nA, the peak PSP value increases from $\sim -51\text{mV}$ to $\sim -21\text{mV}$ with duration time increases from 7ms to 42ms. While for spike amplitude of 10nA, peak PSP value increases from $\sim -41\text{mV}$ to $\sim 21\text{mV}$. In nerve system, synapse will be depolarized to initiate an action potential when the membrane potential arrives at a critical threshold value [33]. Generally, the threshold potential ranges between -50 and -55 mV. The membrane potential can increase or decrease through sodium and potassium ions. An influx of sodium into the cell through voltage-gated sodium channels can depolarize the membrane and excite it. While an efflux of potassium or influx of chloride can hyperpolarize the cell and inhibit the threshold from being reached [35, 36]. In our case, the proposed device can be connected to a neuron circuit which sets the threshold value at 0V. When the potential is above the threshold, the neuron circuit would fire an action potential. On the contrary, the neuron circuit would not fire an action potential. It is observed that a longer spike duration time is needed to activate the artificial synapse at lower spike amplitude. For current spike with amplitude of 10nA, the spike duration time is only $\sim 28\text{ms}$ to fire an action potential. While for current spike with amplitude of 8nA, the spike duration time increases to $\sim 40\text{ms}$ to fire an action potential. In nerve system, accumulative effect is observed on the action potential, i.e., short-term plasticity [7, 49-51]. Such behavior can also be mimicked on our artificial synaptic membrane. Figure 5d and 5e illustrates

membrane potential responses triggered by one and three current spikes, respectively. We have applied three current spikes (5nA, 42ms) with interval time of ~100ms on the gate. It is observed that a single current spike is not sufficient to depolarize the artificial synaptic membrane to fire an action potential. A peak PSP value of ~ -19mV is obtained. While after applying three current spikes, the peak PSP value increases to ~9mV, indicating the depolarization. Here, a decay in PSP is observed after the spiking due to the inherent properties for proton migration. It should be noted here that the temporally coupled characteristics in Figure 5e enable artificial synaptic membrane capable of emulating short-term plasticity behavior. Figure S6 illustrates a typical PSP response stimulated with two successive positive current spikes (30nA, 14ms) with an interval time of ~350ms. The first absolute PSP value (A_1) is ~106mV, while the second absolute PSP value (A_2) is ~127mV. Thus, the PPF Index ($100\% \times A_2/A_1$) is estimated to be ~120%. Such short-term synaptic plasticities make the artificial synaptic membrane potential neuromorphic system applications.

In the present work, Hodgkin-Huxley based artificial synaptic membrane was proposed by using PSG electrolyte gated oxide EDL neuromorphic transistor. Device scalabilities and energy consumptions are needed to be considered to build neuromorphic network. The oxide EDL transistors can potentially realize global connectivity through electrolyte gating, which benefits the construction of neuromorphic network [30]. In our case, electrolyte films are composed of PSG nanoparticles with size of several nanometers. Thus, PSG gated synaptic device could be scaled down to sub-100 nm. The integration density can increase to as high as 10^{10} devices per-centimeter square. One of the most interesting properties for the nanogranular PSG based electrolyte film is its proton conductivities and lateral EDL effects. Thus, synaptic device with multi-gates would be helpful for realizing dendrite integration on single synaptic device without the need of complicated hardware connections [52]. Due to the lateral EDL effects, 3D neuromorphic devices and systems can be established with the

optimized structure. Energy consumption for the proposed artificial synaptic membrane device is also estimated. As shown in Figure 4d, the energy consumption for a single EPSP event is estimated to be as low as $\sim 14\text{pJ}$ ($\sim 1/2 \times 20\text{nA} \times 14\text{ms} \times 100\text{mV}$). When the device is scaled down to sub-100 nm scale, it is possible to decrease the power consumption to sub-fJ level for a single EPSP event. Furthermore, the statistic power is estimated to be below $\sim 70\text{pW}$ ($70\text{mV} \times 1\text{nA}$). When the device is scaled down to sub-100nm scale, it is possible to decrease the power consumption to sub-fW level. Considering that a human brain owns $\sim 10^{15}$ synapses, each containing pre- and post-membranes, energy consumption with the integrity at the same level is estimated to be in the order of 10W, which is comparable to that of a human brain.

In summary, proof-of-principle Hodgkin–Huxley artificial synaptic membrane is proposed for the first time based on inorganic proton conductor in a transistor configuration. PSG-based proton conductor electrolyte demonstrated unique short-term volatile charging behaviors, indicating potential short-term synaptic plasticity applications. Synaptic membrane potential responses were mimicked on the proposed Hodgkin–Huxley artificial synaptic membrane, such as resting membrane potential, excitatory/inhibitory post-synaptic potential (EPSP/IPSP) responses, depolarization responses, etc. At last, scalability and energy consumption of the proposed artificial synaptic membrane were discussed, indicating great potential for brain-inspired cognitive system applications. The proposed Hodgkin–Huxley artificial synaptic membrane provides a new prototype for neuromorphic system applications.

Experimental Section

Fabrication of IWO neuromorphic transistors.

IWO Neuromorphic transistors were fabricated at room temperature. Figure S1 schematically shows the fabrication processing. Firstly, nanogranular PSG based electrolyte films were

deposited on indium tin oxide (ITO) glass substrate by plasma enhanced chemical vapor deposition (PECVD) using SiH_4/PH_3 mixture and O_2 as reactive gases. Then, patterned IWO films were deposited on the PSG electrolyte by radio-frequency magnetron sputtering using IWO ceramic target ($\text{In}_2\text{O}_3:\text{WO}_3=90:10\text{wt}\%$) in Ar ambient with a metal shadow mask. Due to the lateral penetration effect, a thin IWO channel can be self-assembled between two patterned IWO films with a distance of $80\mu\text{m}$. When the distance is $300\mu\text{m}$, isolated patterned IWO films can be obtained. Such in-plane patterns can act as in-plane gates.

Fabrication of IWO/PSG/ITO and IWO/ $\text{SiO}_2/\text{p}^{++}\text{-Si}$ MIM capacitors.

We have sputtered IWO patterns on PSG film coated ITO glass substrate to obtain an IWO/PSG/ITO MIM capacitor for analyzing capacitance and proton conductivity of as-deposited PSG electrolyte. We have also sputtered IWO patterns on commercial available thermally oxidized SiO_2 coated $\text{p}^{++}\text{-Si}$ wafer to obtain an IWO/ $\text{SiO}_2/\text{p}^{++}\text{-Si}$ MIM capacitor for comparison.

Design of artificial synaptic membrane.

One in-plane gate is short connected to the drain and is biased with a current spike. While another in-plane gate is biased at a constant negative voltage. Drain potential can be measured to mimic the membrane potential. Thus, an artificial synaptic membrane is obtained.

Statistical Analysis

The size and the thickness of the sputtered IWO patterns are $150\mu\text{m}\times 1000\mu\text{m}$ and $\sim 120\text{nm}$, respectively. The distance between two neighboring electrodes is $300\mu\text{m}$. The distance between source and drain is $80\mu\text{m}$. The channel length and channel width are $80\mu\text{m}$ and 1mm , respectively. Proton conductivity and frequency-dependent capacitance of the PSG based electrolyte film were measured by a Solartron 1260 impedance analyzer in air ambient. The DC bias and AC bias are set to 0.1V and 0.01V , respectively. Transistor performances are characterized by a Keithley4200 semiconductor parameter analyzer. Transfer curves is

obtained with a constant V_{DS} at 1.5V. V_{GS} is swept from -1.5V to +1.5V at a sweeping rate of $0.05V\ s^{-1}$. Current spike triggered potentials on the MIM capacitor, the IWO neuromorphic transistor and the artificial synaptic membrane were also measured with semiconductor parameter analyzer. Current spike amplitude increases from 5nA to 60nA. The spike width increases from 7ms to 42ms. Negative spike with amplitude of -20nA is also used. All the measurements were performed in a shielded dark box at room temperature with air relative humidity of ~60%. The measured curves were fitted by Matlab using differential equation between the applied current $I(t)$ and the obtained potential response $U(t)$, as shown in Supplementary Information (SI-5).

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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References

- [1] S.Z.Bisri, S.Shimizu, M.Nakano, Y.Iwasa, *Adv.Mater.* **2017**, 29, 1607054.
- [2] H.Chun, T.D.Chung, *Ann.Rev.Anal.Chem.* **2015**, 8, 441.
- [3] N.P.Lu, P.F.Zhang, Q.H.Zhang, R.M.Qiao, Q.He, H.B.Li, Y.J.Wang, J.W.Guo, D.Zhang, Z.Duan, Z.L.Li, M.Wang, S.Z.Yang, M.Z.Yan, E.Arenholz, S.Y.Zhou, W.L.Yang, L.Gu, C.W.Nan, J.Wu, Y.Tokura, P.Yu, *Nature*. **2017**, 546, 124.
- [4] E.Piatti, Q.H.Chen, J.T.Ye, *Appl. Phys. Lett.* **2017**, 111, 013106.
- [5] D.A.Drachman, *Neurology*. **2005**, 64, 2004.

- [6] G.Q.Bi, M.M.Poo, *J. Neurosci.* **1998**, *18*, 10464.
- [7] G.Voglis, N.Tavernarakis, *EMBO Rep.* **2006**, *7*, 1104.
- [8] E.R.Kandel. *Science.* **2001**, *294*, 1030.
- [9] L.F.Abbott, W.G.Regehr, *Nature.* **2004**, *431*, 796.
- [10] J.J.Harris, R.Jolivet, D.Attwell, *Neuron.* **2012**, *75*, 762.
- [11] C.Bartolozzi, G.Indiveri, *Neural Comput.* **2007**, *19*, 2581.
- [12] S.Furber, *IEEE Spectrum.* **2012**, *49*, 44.
- [13] J.J.Yang, M.D.Pickett, X.Li, D.A.A.Ohlberg, D.R.Stewart, R.S.Williams, *Nat. Nanotechnol.* **2008**, *3*, 429.
- [14] S.H.Jo, T.Chang, I.Ebong, B.B.Bhadviya, P.Mazumder, W.Lu, *Nano.Lett.* **2010**, *10*, 1297.
- [15] T.Hasegawa, T.Ohno, K.Terabe, T.Tsuruoka, T.Nakayama, J.K.Gimzewski, M.Aono, *Adv.Mater.* **2010**, *22*, 1831.
- [16] S.J.Choi, G.S.Park, K.H.Kim, S.Cho, W.Y.Yang, X.S.Li, J.H.Moon, K.J.Lee, K.Kim, *Adv.Mater.* **2011**, *23*, 3272.
- [17] H.J.Koo, J.H.So, M.D.Dickey, O.D.Velev, *Adv.Mater.* **2011**, *23*, 3559.
- [18] R.Hosseini, J.S.Lee, *ACS Nano.* **2015**, *9*, 419.
- [19] S.Park, M.Chu, J.Kim, J.Noh, M.Jeon, B.H.Lee, H.Hwang, B.Lee, B.G.Lee, *Sci.Rep.* **2015**, *5*, 10123.
- [20] P.M.Sheridan, F.X.Cai, C.Du, W.Ma, Z.Y.Zhang, W.D.Lu, *Nat. Nanotechnol.* **2017**, *12*, 784.
- [21] K.Ueno, S.Nakamura, H.Shimotani, A.Ohtomo, N.Kimura, T.Nojima, H.Aoki, Y.Iwasa, M.Kawasaki, *Nat. Mater.* **2008**, *7*, 855.
- [22] Y.Yamada, K.Ueno, T.Fukumura, H.T.Yuan, H.Shimotani, Y.Iwasa, L.Gu, S.Tsukimoto, Y.Ikuhara, M.Kawasaki, *Science.* **2011**, *332*, 1065.

- [23] S.H.Kim, K.Hong, W.Xie, K.H.Lee, S.P.Zhang, T.P.Lodge, C.D.Frisbie, *Adv.Mater.* **2013**, 25, 1822.
- [24] S.Bubel, M.S.Menyo, T.E.Mates, J.H.Waite, M.L.Chabiny, *Adv.Mater.* **2015**, 27, 3331.
- [25] K.Kim, C.L.Chen, Q.Truong, A.M.Shen, Y.Chen, *Adv. Mater.* **2013**, 25, 1693.
- [26] L.Q.Zhu, C.J.Wan, L.Q.Guo, Y.Shi, Q.Wan, *Nat. Commun.* **2014**, 5, 3158.
- [27] Y.H.Liu, L.Q.Zhu, P.Feng, Y.Shi, Q.Wan, *Adv. Mater.* **2015**, 27, 5599.
- [28] P.Gkoupidenis, N.Schaefer, B.Garlan, G.G.Malliaras, *Adv. Mater.* **2015**, 27, 7176.
- [29] C.J.Wan, L.Q.Zhu, Y.H.Liu, P.Feng, Z.P.Liu, H.L.Cao, P.Xiao, Y.Shi, Q.Wan, *Adv. Mater.* **2016**, 28, 3557.
- [30] P.Gkoupidenis, D.A.Koutsouras, G.G.Malliaras, *Nat. Commun.* **2017**, 8, 15448.
- [31] W.Gerstner, W.M.Kistler, *Spiking Neuron Models: Single Neurons, Populations, Plasticity. Cambridge University Press.* **2002**.
- [32] G.Edwards, K.A.Dora, M.J.Gardener, C.J.Garland, A.H.Weston, *Nature.* **1998**, 396, 269.
- [33] C.Callies, J.Fels, I.Liashkovich, K.Kliche, P.Jeggle, K.Kusche-Vihrog, H.Oberleithner, *J.Cell Sci.* **2011**, 124, 1936.
- [34] J.M.Diamond, E.M.Wright, *Ann.Rev.Physiol.* **1969**, 31, 581.
- [35] G.Stuart, N.Spruston, B.Sakmann, M.Hausser, *Tren. Neurosci.* **1997**, 20, 125.
- [36] H.Bostock, K.Cikurel, D.Burke, *Muscle & Nerve.* **1998**, 21, 137.
- [37] W.S.Mcculloch, W.Pitts, *Bull.Math.Biophys.* **1943**, 5, 115.
- [38] A.L.Hodgkin, A.F.Huxley, *J.Physiol.* **1952**, 117, 500.
- [39] A.M.Simon, P.Doran, R.Paterson, *J.Membr.Sci.* **1996**, 109, 231.
- [40] M.D.Pickett, G. Medeiros-Ribeiro, R.S.Williams, *Nat.Mater.* **2013**, 12, 114.
- [41] J.S.Coombs, J.C.Eccles, P.Fatt, *J.Physiol.* **1955**, 130, 374.
- [42] S.E.Fortune, G.J.Rose, *Trends Neurosci.*, **2001**, 24, 381
- [43] J.Shi, S.D.Ha, Y.Zhou, F.Schoofs, S.Ramanathan, *Nat. Commun.* **2013**, 4, 2676.

- [44] J.Shi, Y.Zhou, S.Ramanathan, *Nat. Commun.* **2014**, *5*, 4860.
- [45] R.M.Empson, M.L.Garside, T.Knopfel, *J.Neurosci.* **2007**, *27*, 3753.
- [46] W.A.Catterall, A.P.Few, *Neuron.* **2008**, *59*, 882.
- [47] H.Markram, J.Lübke, M.Frotscher, B.Sakmann, *Science.* **1997**, *275*, 213.
- [48] A.L.Person, D.J.Perkel, *Neuron.* **2005**, *46*, 129.
- [49] R.S.Zucker, W.G.Regehr, *Ann.Rev.Nueronsci.* **2002**, *64*, 335.
- [50] M.A.Mukhamedyarov, S.N.Grishin, A.L.Zefirov, A.Palotás, *Pflugers Arch - Eur. J. Physiol.* **2009**, *458*, 563.
- [51] M.Yoneyama, Y.Fukushima, M.Tsukada, T.Aihara, *Cogn.Neuronsci.* **2011**, *5*, 333.
- [52] L.Q.Zhu, H.Xiao, Y.H.Liu, C.J.Wan, Y.Shi, Q.Wan, *Appl.Phys.Lett.* **2015**, *107*, 143502

The table of contents entry:

Hodgkin-Huxley artificial synaptic membrane is proposed based on protonic/electronic hybrid oxide neuromorphic transistor. Typical resting potential, excitatory/inhibitory post-synaptic potential and membrane depolarization/activation behaviors are mimicked. Proton related electrostatic coupling enables the neuromorphic transistor to possess short-term synaptic plasticities with low power consumption. The results provide a new prototype for neuromorphic cognitive system applications.

Keyword: Protonic/electronic hybrid, Neuromorphic transistors, Artificial synaptic membrane, Synaptic plasticity

Yang Ming Fu, Chang Jin Wan, Li Qiang Zhu*, Hui Xiao, Xiao Dong Chen*, Qing Wan*

Hodgkin–Huxley Artificial Synaptic Membrane Based on Protonic/Electronic Hybrid Neuromorphic Transistors

ToC figure