Cell-Like Behaviors of Dynamic Graphene Bubbles with Fast Water Transport

Tian Li,† Wenyu Sun,† Xinqi Wang,† Jingqi Feng, and Donglin Ma*

ABSTRACT: Ultrafast water transport in graphitic nanoenvironment is fundamentally important in the research of biomimetic membranes for potential applications in separation and energy. Yet, the form of graphitic nanostructures has not been fully explored with only carbon nanotubes and graphene nanochannels reported. Here, we fabricated dynamic graphene bubbles via strain engineering of chemical vapor deposition (CVD)-grown graphene on metal substrates. These graphene bubbles could switch between an inflated state and a deflated state continuously with the control of environmental moisture flow. It is demonstrated that water vapors transport through graphene wrinkles and condense inside graphene bubbles. The water transport rates across these graphene bubbles were calculated via dynamic Newton rings, which is comparable to that of carbon nanotubes and aquaporin. The discovery of dynamic graphene bubbles hosting the ability of fast water transport is helpful for an advanced understanding of the nanofluidic phenomenon and its future applications.

INTRODUCTION

Biological cells are highly efficient at transporting water across their membranes due to the presence of specific membrane proteins, for instance, aquaporins, which provide nanofluidic channels for ultrafast water transport. Learning from the structure evolved by nature over a billion years, developing artificial channel based biomimetic membranes has attracted great interest in recent years for its potential application in water desalination or harvesting energy.3

Graphitic nanostructures with artificial channels are ideal candidates for understanding the biological nanofluidic phenomena. It has been demonstrated that carbon nanotubes exhibit rapid and selective water transport through their confined spaces, which are much higher than the conventional Hagen–Poiseuille flow. Efforts have been intensively made to understand the physics behind using experiments and theoretical simulations, demonstrating a similar mechanism to that of aquaporins. Moreover, the enhancement of water transport was also found in graphene-based nanostructures, such as graphene/SiO2 nanochannels, graphene oxide films, graphene/silicon carbide, and porous graphene. Compared to that of carbon nanotubes, the water transport in graphene-based nanostructures could be delicately tuned by external conditions such as graphene surface charges, substrate effect, and graphene morphologies. Thus, the exploration of new graphene-based nanostructures hosting the ability of fast water transport is appealing for an advanced understanding of the nanofluidic phenomenon and its future applications like lab-on-a-chip.

Graphene bubble is a unique graphene-based nanostructure holding a mesoscopic volume of gas or liquid on a substrate. Graphene bubble has been reported to exhibit various new properties beyond intrinsic graphene, such as pseudomagnetic field and Raman oscillation. Previous research studies mainly focused on static bubbles, which are stable against instrument detection and environment. In this work, we report the fabrication of dynamic graphene bubbles on Cu/W alloy substrate through mechanical bending, which accumulates enough strains to locally delaminate the as-grown graphene from their metal substrate. Evidence shows that some of the strain-induced graphene bubbles could inflate and deflate in the micrometer scale with the control of environmental moisture flow. It is indicated that water vapors could transport through graphene wrinkles/defects and condense inside graphene bubbles. The water transport rates across these graphene bubbles were calculated from measurements of dynamic Newton rings.

Received: August 27, 2020
Accepted: October 5, 2020
Published: October 20, 2020
RESULTS AND DISCUSSION

The fabrication process is schematically shown in Figure 1A−C. A 25 μm thick Cu foil on the supporting 0.05 mm thick W foil was employed as the growth substrate, and methane was used as the carbon precursor for graphene growth. The growth temperature was 1090 °C. After growth, the Cu foils melted and evenly covered the surface of W, resulting in an optically smooth surface (Figure 1D). The as-grown graphene samples were transferred onto SiO2/Si substrate through the wet etching method for characterization. Most regions show deeper contrasts compared to the light contrast of monolayer graphene (inset of Figure 1D). The result implies that the as-grown graphene is a multilayer. Raman spectrum further shows a typical G peak and a two-dimensional (2D) peak at 1580 and 2700 cm−1 with a ratio of less than 1:2 (Figure S1), respectively. It is confirmed that twisted bi- or trilayers graphene were obtained.

Direct bending process is applied to the Cu/W substrates with a bending radius of ~1.1 cm (Figure 1E). Due to the rigidity of the Cu/W substrate, the local strain could efficiently accumulate on the surface of the sample, resulting in the change of surface morphologies (Figure 1B,C). The optical image in Figure 1F clearly shows that several trenches along the bending direction appeared on the sample surface after the bending process. Interestingly, amounts of circle contrast with 1−5 μm sizes were observed around these trenches. It is speculated that some graphene bubbles emerged after the bending process. Atomic force microscopy was used to further characterize these circle contrast. Two types of bubbles were observed on the surface. As shown in Figure 1G, one type of bubbles has clear fringes and a semisphere morphology with a nm-scale smooth surface, the bubble with a 1.5 μm lateral size has a maximum height of ~600 nm. This is a typical static graphene bubble, which is similar to the literature reports.28,29,35 The other type of graphene bubbles is less observable compared to the previous one. As shown in Figure 1H,I, the bubble still shows a circle contrast with a similar lateral size but with a much lower height of ~20 nm. The fringes of the bubble are blurred and the surface is corrugated. The latter one is more likely to be a deflated state of "balloon", suggesting some graphene bubbles collapsed on the surface.

We exposed the sample to a humidity-controlled environment and in situ monitor the morphology changes of the bubbles under an optical microscope. Under ambient conditions (room temperature; relative humidity (RH) ~25%), the bubble is in a deflated state, as shown in Figure 2A. When the sample was exposed to moisture flow with RH ~60% for 2 s, we observed that the bubble gradually inflated into a quasi-stable semisphere (Figure 2B). When the moisture flow was cut off, the inflated graphene bubbles gradually shrank, finally collapsing into a deflated state (Figure 2C). The inflation and deflation process of the graphene bubble could be repeated for several cycles (two and a half cycles in 10 s) with control of the RH condition.

Figure 1. Graphene growth and the fabrication of graphene bubbles. (A−C) Schematic illustration of the strain engineering of the as-grown graphene on growth substrates. (D) Optical image of Cu/W substrate after growth. The inset is the optical image of graphene samples transferred onto SiO2/Si. (E) Bending process of the Cu/W substrates. (F) Optical image of the surface of Cu/W substrate after the bending process. (G) Atomic force microscopy (AFM) image of a static graphene bubble. The inset is the height profile of the graphene bubble. The scale bars of (D, F) and (G−I) are 100 μm and 500 nm, respectively.

Figure 2. Environmental response behavior of the dynamic graphene bubbles. (A, C, E) Schematic illustrations and optical images of a graphene bubble under ambient conditions (room temperature; relative humidity (RH) ~25%). (B, D) Schematic illustrations and optical images of the graphene bubble exposed to moisture flow (relative humidity (RH) ~60%). The scale bar is 20 μm.
It is also observed that some surface features inside the graphene bubbles were magnified optically in the inflation process (Figure S2). The evidence strongly suggests that the water vapor could transport across the graphene bubble in response to the environment humidity. It is also noted that the inflated state of the graphene bubble barely changed in several cycles, while the deflated states of the graphene bubble were totally different in morphologies. It is speculated that the collapsing and folding of the graphene membrane is random as well as the trapping of residual water. Movie S1 shows the inflation and deflation processes of one dynamic graphene bubble captured by a high-speed camera.

Raman characterization of the dynamic graphene bubbles provides more information about the water penetration process. As shown in Figure 3A,B, the Raman spectrum outside the graphene bubble shows a 2D peak of graphene (~2700 cm\(^{-1}\)) and a broadened photoluminescence peak around 1200 cm\(^{-1}\), which originated from the effect of the Cu substrate.\(^{39}\) However, the spectrum inside the bubble (Figure 3C) shows an obvious shift of a Cu-induced photoluminescence peak to ~2000 cm\(^{-1}\), which may be attributed to the presence of copper oxide.\(^{39} \) Moreover, two characteristic peaks at 623 and 980 cm\(^{-1}\) were observed inside the graphene bubble. The line profile of the peak intensity (~980 cm\(^{-1}\)) clearly shows that the signal is barely observed outside the bubble but localized inside the bubble. These peaks are attributed to the presence of CuO\(_x\) and WO\(_x\).\(^{40,41}\) The results indicate that water has been transported into the interface of graphene and metal substrate, and residual water inside graphene bubbles may cause a local electrochemical oxidation process, leading to the formation of metal oxides.

As shown in Figure 4A,B, the optical microscope with a 633 nm monochromatic filter enables us to observe the dynamic Newton rings of graphene bubbles during the inflation and deflation processes. The time-dependent evolution of Newton rings provides an alternative way to quantitatively describe the water transport process across the graphene bubble. The volume of graphene bubbles could be estimated as a spherical crown

\[ V = \pi H \left( \rho - \frac{H}{3} \right) \]

where \( V \) is the volume, \( H \) is the height, \( \rho \) is the curvature radius, and \( R \) is the bottom radius of the graphene bubble.

The curvature radius of graphene bubbles could be calculated by the measurement of the Newton ring

\[ \rho = \frac{d_{k+m}^2 - d_k^2}{4m\lambda} \]

where \( d_k \) and \( d_{k+m} \) are fringe orders of the Newton ring of the graphene bubbles, \( m \) is the order difference between \( d_k \) and \( d_{k+m} \), \( \lambda \) is the wavelength of the incident light, and \( n \) is the refractive index of the water filling graphene bubbles (water in this case).

The rates of water transport across graphene bubbles can be estimated by calculating the volume change of the graphene bubble between each frame of the camera record (20 ms). The inlet and outlet rates of water transport of fifteen graphene bubbles were calculated using the above method, as shown in Figure 4C. The average rate of water transport across graphene bubbles on Cu/W substrate is \( \sim 100 \mu m^3 \text{ ms}^{-1} \), with no significant differences between samples and also no differences in inlet/outlet rates.

It is surprising to find that the value is only 1–2 magnitude order smaller than the rate of water transport in carbon nanotubes\(^9\) and aquaporin,\(^{42}\) much faster than that in trans-
ferred graphene/SiO$_2$\textsuperscript{16} and chemical vapor deposition (CVD)-grown graphene/Cu\textsuperscript{43} as shown in Figure 4D. It is reasonable to consider that there shall be some channel-like nanostructures, similar to carbon nanotubes, around the dynamic graphene bubbles, which realize the fast water transport in this system. As shown in Figure 4E,F, AFM characterization reveals that graphene wrinkles with a height of 20–30 nm coexist with these graphene bubbles, suggesting the graphene wrinkles serve as nanochannels for fast water transport. We further deduce that the driving force of water transport into graphene bubbles is the hydrophilic nature of the interface of graphene and Cu/W substrates, which is more energy-favorable for water occupation with the assistance of graphene covering\textsuperscript{43}.

CONCLUSIONS

We report the fabrication of dynamic graphene bubbles on the Cu/W alloy substrate through mechanical bending. Evidence shows that some of the strain-induced graphene bubbles respond to environmental moisture flow, proving water vapors could transport through graphene bubbles and condense inside graphene bubbles. The water transport rates across these graphene bubbles were calculated via measurement of dynamic Newton rings and the value is compared to that of carbon nanotubes and aquaporin, suggesting that graphene wrinkles could also serve as artificial channels for fast water transport. Our work provides a new platform to study the nanofluidic phenomenon and shed light on its possible applications in humidity sensing.

EXPERIMENTAL SECTION

Synthesis of Graphene on Cu–W Substrate. The compounds were synthesized in a horizontal tube furnace (Hefei Kejing OTF-1200X CVD system). The width of the furnace is about 40 cm, and the length of the horizontal tube is about 120 cm. H$_2$ (100–500 sccm) was used as the carrier gas. Before growth, a 1 cm × 1 cm W foil (thickness: 0.05 mm) with a copper foil (thickness: 0.025 mm) on the top was placed on a quartz boat, which was placed at the center of the tube. The sample was heated to the growth temperature of 1090 °C with a ramp rate of 15 °C min$^{-1}$. CH$_4$ (20 sccm) was supplied after the temperature was stable for 5 min. Finally, after a 10 min growth, the system was cooled naturally to room temperature.
Optical Microscope (OM). Optical microscopy images were taken by a CX40 microscope (Sunny Optical Technology (Group) CO., LTD) with a 633 nm monochromatic filter.

Atomic Force Microscopy (AFM). AFM measurements were performed using a Bruker Dimension Icon AFM. The images were taken in ScanAsyst-air mode with a ScanAsyst-air AFM tip.

Raman Spectroscopy. The measurements were performed using a Horiba LabRAM HR-800 Raman spectrometer. A 633 nm laser source with an intensity of 0.45 mW at the sample position was utilized.

ASSOCIATED CONTENT

1. Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.0c04150.

Raman spectrum of the as-grown graphene on the SiO₂/Si substrate and sequential optical images of a dynamic graphene bubble (PDF)

Movie S1: High-speed camera movie of the inflation and deflation processes of a dynamic graphene bubble (MP4)

(APDF)

AUTHOR INFORMATION

Corresponding Author
Donglin Ma – Department of Physics, Capital Normal University, Beijing 100048, People’s Republic of China; orcid.org/0000-0002-0536-1871; Email: madonglin@cnu.edu.cn

Authors
Tian Li – Department of Physics, Capital Normal University, Beijing 100048, People’s Republic of China; orcid.org/0000-0002-9687-2289
Wenwu Sun – Department of Physics, Capital Normal University, Beijing 100048, People’s Republic of China
Xinqi Wang – Department of Physics, Capital Normal University, Beijing 100048, People’s Republic of China
Jingqi Feng – Department of Physics, Capital Normal University, Beijing 100048, People’s Republic of China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c04150

Author Contributions
'T.L., W.S., and X.W. contributed equally to this work.

Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by the Beijing Natural Science Foundation (Z190011), the Capacity Building for Sci-Tech Innovation-Fundamental Scientific Research Funds (20530290025 and 20530290057), the Academy for Multidisciplinary Studies (Capital Normal University), and the National Natural Science Foundation of China (11704279).

REFERENCES

(1) Verkman, A. S.; van Hoek, A. N.; Ma, T.; Frigeri, A.; Skach, W. R.; Mitra, A.; Tamarappoo, B. K.; Farinas, J. Water Transport across Mammalian Cell Membranes. Am. J. Physiol.: Cell Physiol. 1996, 270, C12–C30.

(2) Ager, P.; Preston, G. M.; Smith, B. L.; Jung, J. S.; Raina, S.; Moon, C.; Guggino, W. B.; Nielsen, S. Aquaporin CHIP: The Archetypal Molecular Water Channel. Am. J. Physiol.: Renal Physiol 1993, 265, F463–F476.

(3) Park, H. G.; Jung, Y. Carbon Nanofluidics of Rapid Water Transport for Energy Applications. Chem. Soc. Rev. 2014, 43, 565–576.

(4) Shen, Y.; Saboe, P. O.; Sines, I. T.; Erbakan, M.; Kumar, M. Biomimetic Membranes: A Review. J. Membr. Sci. 2014, 454, 359–381.

(5) Picallo, C. B.; Gravelle, S.; Joly, L.; Charlaix, E.; Bocquet, L. Nanofluidic Osmotic Diodes: Theory and Molecular Dynamics Simulations. Phys. Rev. Lett. 2013, 111, No. 245401.

(6) Liu, H.; He, J.; Tang, J.; Liu, H.; Pang, P.; Cao, D.; Krestic, P.; Joseph, S.; Lindsay, S.; Nuckolls, C. Translocation of Single-Stranded DNA Through Single-Walled Carbon Nanotubes. Science 2010, 327, 64–67.

(7) Babu, J. S.; Sathian, S. P. The Role of Activation Energy and Reduced Viscosity on the Enhancement of Water Flow through Carbon Nanotubes. J. Chem. Phys. 2011, 134, No. 194509.

(8) Corry, B. Designing Carbon Nanotube Membranes for Efficient Water Desalination. J. Phys. Chem. B 2008, 112, 1427–1434.

(9) Majumder, M.; Choppa, N.; Andrews, R.; Hinds, B. J. Enhanced Flow in Carbon Nanotubes. Nature 2005, 438, 44.

(10) Holt, J. K. Fast Mass Transport through Sub-2-Nanometer Carbon Nanotubes. Science 2006, 312, 1034–1037.

(11) Joseph, S.; Aluru, N. R. Why Are Carbon Nanotubes Fast Transporters of Water? Nano Lett. 2008, 8, 452–458.

(12) Srivastava, A.; Srivastava, O. N.; Talapatra, S.; Vajtai, R.; Ajayan, P. M. Carbon Nanotube Filters. Nat. Mater. 2004, 3, 610–614.

(13) Secchi, E.; Marbach, S.; Nigües, A.; Stein, D.; Siria, A.; Bocquet, L. Massive Radius-Dependent Flow Slippage in Carbon Nanotubes. Nature 2016, 537, 210–213.

(14) Cao, Z.; Peng, Y.; Yan, T.; Li, S.; Li, A.; Voth, G. A. Mechanism of Fast Proton Transport along One-Dimensional Water Chains Confined in Carbon Nanotubes. J. Am. Chem. Soc. 2010, 132, 11395–11397.

(15) Falk, K.; Sedlmeier, F.; Joly, L.; Netz, R. R.; Bocquet, L. Molecular Origin of Fast Water Transport in Carbon Nanotube Membranes: Superlubricity versus Curvature Dependent Friction. Nano Lett. 2010, 10, 4067–4073.

(16) Suk, M. E.; Aluru, N. R. Water Transport through Ultrathin Graphene. J. Phys. Chem. Lett. 2010, 1, 1590–1594.

(17) Kalra, A.; Garde, S.; Hummer, G. Osmotic Water Transport through Carbon Nanotube Membranes. Proc. Natl. Acad. Sci. U.S.A. 2003, 100, 10175–10180.

(18) Xie, Q.; Alibakhshi, M. A.; Jiao, S.; Xu, Z.; Hempel, M.; Kong, J.; Park, H. G.; Duan, C. Fast Water Transport in Graphene Nanofluidic Channels. Nat. Nanotech. 2018, 13, 238–245.

(19) Lee, D.; Ahn, G.; Ryu, S. Two-Dimensional Water Diffusion at a Graphene–Silica Interface. J. Am. Chem. Soc. 2014, 136, 6634–6642.

(20) Akbari, A.; Sheath, P.; Martin, S. T.; Shinde, D. B.; Shaibani, M.; Banerjee, P. C.; Tkacz, R.; Bhattacharyya, D.; Majumder, M. Large-Area Graphene-Based Nanofiltration Membranes by Shear Alignment of Discotic Nematic Liquid Crystals of Graphene Oxide. Nat. Commun. 2016, 7, No. 10891.

(21) Wei, N.; Peng, X.; Xu, Z. Breakdown of Fast Water Transport in Graphene Oides. Phys. Rev. E 2014, 89, No. 012113.

(22) Kidambi, P. R.; Boutilier, M. S. H.; Wang, L.; Jang, D.; Kim, J.; Karnik, R. Selective Nanoscale Mass Transport across Atomically Thin Single Crystalline Graphene Membranes. Adv. Mater. 2017, 29, No. 1605896.

(23) Gai, J.-G.; Gong, X.-L.; Wang, W.-W.; Zhang, X.; Kang, W.-L. An Ultrafast Water Transport Forward Osmosis Membrane: Porous Graphene. J. Mater. Chem. A 2014, 2, 4023.

(24) Celebi, A. T.; Barisik, M.; Besok, A. Surface Charge-Dependent Transport of Water in Graphene Nano-Channels. Microfluid. Nanofluid. 2018, 22, No. 7.

(25) Liu, B.; Wu, R.; Law, A. W.-K.; Peng, X.-Q.; Bai, L.; Zhou, K. Channel Morphology Effect on Water Transport through Graphene Bilayers. Sci. Rep. 2016, 6, No. 38583.

(26) Yue, K.; Gao, W.; Huang, R.; Liechti, K. M. Analytical Methods for the Mechanics of Graphene Bubbles. J. Appl. Phys. 2012, 112, No. 083512.
(27) Stolyarova, E.; Stolyarov, D.; Bolotin, K.; Ryu, S.; Liu, L.; Rim, K. T.; Klima, M.; Hybertsen, M.; Pogorelsky, I.; Pavlishin, I.; Kusche, K.; Hone, J.; Kim, P.; Stormer, H. L.; Yakimenko, V.; Flynn, G. Observation of Graphene Bubbles and Effective Mass Transport under Graphene Films. Nano Lett. 2009, 9, 332−337.

(28) Georgiou, T.; Britnell, L.; Blake, P.; Gorbachev, R. V.; Gholinia, A.; Geim, A. K.; Casiraghi, C.; Novoselov, K. S. Graphene Bubbles with Controllable Curvature. Appl. Phys. Lett. 2011, 99, No. 093103.

(29) Zabel, J.; Nair, R. R.; Ott, A.; Georgiou, T.; Geim, A. K.; Novoselov, K. S. Raman Spectroscopy of Graphene and Bilayer under Biaxial Strain: Bubbles and Balloons. Nano Lett. 2012, 12, 617−621.

(30) Ghorbanfekr-Kalashami, H.; Vasu, K. S.; Nair, R. R.; Peeters, F. M.; Neek-Amal, M. Dependence of the Shape of Graphene Nanobubbles on Trapped Substance. Nat. Commun. 2017, 8, No. 15844.

(31) Bao, Q.; Chen, J.; Xiang, Y.; Zhang, K.; Li, S.; Jiang, X.; Xu, Q.-H.; Loh, K. P.; Venkatesan, T. Graphene Nanobubbles: A New Optical Nonlinear Material. Adv. Opt. Mater. 2015, 3, 744−749.

(32) Jain, S.; K.; Juricic, V.; Barkema, G. T. Probing the Shape of a Graphene Nanobubble. Phys. Chem. Chem. Phys. 2017, 19, 7465−7470.

(33) Khestanova, E.; Guinea, F.; Fumagalli, L.; Grigorieva, I. V. Universal Shape and Pressure inside Bubbles Appearing in van Der Waals Heterostructures. Nat. Commun. 2016, 7, No. 12587.

(34) Levy, N.; Burke, S. A.; Meaker, K. L.; Panlasigui, M.; Zettl, A.; Guinea, F.; Neto, A. H. C.; Crommie, M. F. Strain-Induced Pseudo-Magnetic Fields Greater Than 300 Tesla in Graphene Nanobubbles. Science 2010, 329, 544−547.

(35) Jia, P.; Chen, W.; Qiao, J.; Zhang, M.; Zheng, X.; Xue, Z.; Liang, R.; Tian, C.; He, L.; Di, Z.; Wang, X. Programmable Graphene Nanobubbles with Three-Fold Symmetric Pseudo-Magnetic Fields. Nat. Commun. 2019, 10, No. 3127.

(36) Huang, Y.; Wang, X.; Zhang, X.; Chen, X.; Li, B.; Wang, B.; Huang, M.; Zhu, C.; Zhang, X.; Bacsza, W. S.; Ding, F.; Ruoff, R. S. Raman Spectral Band Oscillations in Large Graphene Bubbles. Phys. Rev. Lett. 2018, 120, No. 186104.

(37) Lu, J.; Neto, A. H. C.; Loh, K. P. Transforming Moiré Blisters into Geometric Graphene Nano-Bubbles. Nat. Commun. 2012, 3, No. 823.

(38) Reina, A.; Son, H.; Jiao, L.; Fan, B.; Dresselhaus, M. S.; Liu, Z.; Kong, J. Transferring and Identification of Single- and Few-Layer Graphene on Arbitrary Substrates. J. Phys. Chem. C 2008, 112, 17741−17744.

(39) Choi, J.; Koo, S.; Song, M.; Jung, D. Y.; Choi, S.-Y.; Ryu, S. Varying Electronic Coupling at Graphene−Copper Interfaces Probed with Raman Spectroscopy. 2D Mater. 2020, 7, No. 025006.

(40) Goldstein, H. F.; Kim, D.; Yu, P. Y.; Bourne, L. C.; Chaminade, J.-P.; Ngunga, L. Raman Study of CuO Single Crystals. Phys. Rev. B 1990, 41, 7192−7194.

(41) Mwakikunga, B. W.; Sideras-Haddad, E.; Forbes, A.; Arendse, C. Raman Spectroscopy of VO₂ Nano-Wires and Thermo-Chromism Study of VO₁ Belts Produced by Ultrasonic Spray and Laser Pyrolysis Techniques. Phys. Status Solidi A 2008, 205, 150−154.

(42) Zeidel, M. L.; Ambudkar, S. V.; Smith, B. L.; Agre, P. Reconstitution of Functional Water Channels in Liposomes Containing Purified Red Cell CHIP28 Protein. Biochemistry 1992, 31, 7436−7440.

(43) Xu, X.; Yi, D.; Wang, Z.; Yu, J.; Zhang, Z.; Qiao, R.; Sun, Z.; Hu, Z.; Gao, P.; Peng, H.; Liu, Z.; Yu, D.; Wang, E.; Jiang, Y.; Ding, F.; Liu, K. Greatly Enhanced Anticorrosion of Cu by Commensurate Graphene Coating. Adv. Mater. 2018, 30, No. 1702944.