Power Generation by Water Transpiration from Microporous Alumina

Manpreet Kaur (✉ randhawamanpreet438@gmail.com)

National Institute for Materials Science <https://orcid.org/0000-0003-3511-7797>

Satoshi Ishii

National Institute for Materials Science <https://orcid.org/0000-0003-0731-8428>

Ryusuke Nozaki

Hokkaido University

Tadaaki Nagao

National Institute for Materials Science <https://orcid.org/0000-0002-6746-2686>

Article

Keywords: Water evaporation, Power generation, Microporous alumina, Water-dielectric interface, Surface polarization

Posted Date: February 5th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-137709/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

Hydropower generation has been the most developed sustainable energy source that is based on the electromagnetic transduction of the gravitational potential energy but is only realized through elaborate construction of water dam and not yet suitable for small-scale energy harvesters. Here, we report that wetting and evaporation of water from a small block of porous alumina can generate electrical current in the direction of water transpiration. This induced current in microporous alumina is associated with the mass transport of water accompanying the accumulated charge near the negatively charged surface of the alumina pore. Without any pre-treatment or additives, once water evaporation commences, a 3×3 cm² piece of alumina generates an open-circuit voltage of up to 0.27 V. Possible influence on power generation of the water-insulator interface and naturally available protons in water are discussed with respect to experimental results. Total output of this novel microporous ceramic electric generator can be scaled up and could be used for stand-alone energy harvesters or power generators in self-powered off-grid agricultural/ industrial sensors.

Introduction

Development of renewable ways to harvest energy from natural sources with practically zero carbon emission has become increasingly important ^{1,2,3}. Efforts in various directions have been made to develop different kinds of power generation systems to convert ubiquitous natural energy to electricity, using solar cells ^{4,5}, thermoelectric ^{6,7} and piezoelectric/triboelectric generators ⁸, as well as nano electric generators ^{8,9}. As seen from these examples, generating sustainable and stable electricity from natural sources usually requires sophisticated hetero-structured materials and complex device configurations ^{10,11,12,13}. Hydropower generation produces about one-sixths of the global electricity without the cost of carbon emission, but it requires large-scale construction with heavy impact on natural environments and requires sophisticated machinery ¹⁴. Recently, evaporation-induced power generation has been attracting great interests as a miniaturized hydropower source which resembles transpiration of water in plants ^{15,16,17,18}. The origin of generated electricity is based on the streaming current of electrolytes, where the movements of charged ions near the surface of a conducting substrate induces a voltage drop associated with evaporating water molecules. The presence of an electrical double layer (EDL) at the interface between the liquid and porous wall forms the basis of charge movement during water evaporation ^{19,20,21}.

In the early demonstrations electrical signals were detected when CNTs were immersed in flowing water or polar liquids ^{22,23,24,25,26}. However, the observed voltage was only microvolts/cm and the fabrication and handling of CNTs is incompatible with large-scale applications. Similarly, it has been observed that a few millivolts can be generated by using carbon black ²⁰, graphene oxide ^{27,28}, monolayer graphene ^{29,30}, as well as carbon-based hybrid systems grown on oxide nanowire networks ³¹ or cellulose-based filter paper printed with multi-walled CNTs ^{32,33}. However, most of these carbon-based materials adhere only weakly to substrates, making devices rather fragile and hard to scale up, and the output voltage was

below 100 mV/cm² range at the largest^{22,27,29,30,34,35}. Recently, several dielectric samples were explored to harvest electricity from water evaporation based on the streaming potential/current mechanism such as natural wood³⁶, oxide nanoparticles-based flexible hydroelectric film^{37,38}, which has widened the variety of device structures as well as increased the feasibility of this approach for the applications.

In this study, we discovered that substantial streaming potential is possible across an alumina “insulator” block soaked in deionized water. Here we propose microporous alumina as a prototypical and efficient power-generating substrate to achieve higher voltage efficiency, driven by water transpiration compared to carbon-based devices. Micro/nano-porous alumina has a long history of applications in optical, chemical, and biological sciences and relevant engineering fields^{39,40,41,42}. The surface chemistry of alumina is essential to its performance as a building block for biosensing⁴³, water desalination⁴⁴, and nanoelectronic devices⁴⁵, as it is chemically stable in aqueous environments and at high temperatures^{46,47}. In this work, we report the use of a robust porous alumina without any pre-treatment or coating for electricity generation driven by water evaporation. Its porosity drives the capillary force and constantly supports transpiration through the block, which results in power generation. A 3.0×3.0×0.3 cm² block shows the capacity to generate an open circuit potential as high as ~0.27 V with a stable power-generating performance exceeding a year under ambient conditions. Among different conditions investigated in our work, the maximum streaming voltage was obtained when one-half of the porous alumina sample was partly soaked in water at an appropriate placement angle. Output power can be flexibly tuned by changing the wetting conditions of the porous medium, water temperature, and salt concentration, as well as by simply altering the connections of the modules in series/parallel. We believe that abundant interconnected pores provide a large dielectric (polarized) alumina surface that produces sufficient charge to yield effective carrier diffusion at the water-alumina interface. This phenomenon is based on evapotranspiration of water and does not require a supply of light or heat. This indicates that the proposed energy harvesting method can work anywhere, anytime on earth, irrespective of the time of day, and making it a true energy-harvesting device. Such electricity generators inaugurate a robust and facile energy-harvesting method, applicable in small-scale power generators for self-powered sensor networks, as well as electricity generators that can operate on cloudy days and at night.

Experimental

Alumina with ~35% porosity was purchased from ASUZAC Fine Ceramics. The chemical composition of alumina was analysed by energy-dispersive X-ray spectroscopy (EDX). Sample morphology was studied by SEM (Hitachi FE-SEM SU8230). X-ray diffractions were taken using a Rigaku Ultima III, Rint 2000. Electrical contact to the alumina was achieved using conductive clamps. Silicone glue was used to prevent a possible electrical short circuit and a clamp was used to hold the sample at a fixed position (Figure 1a). Electrical measurements were taken with VersaSTAT potentiometer (VersaSTAT 4, Princeton Applied Research) under water evaporation. The specific surface area was measured using the Brunauer–Emmett–Teller (BET) method (Quantachrome, Autosorb-iQ). The alumina was characterized with an inductively coupled plasma optical emission spectrometer (ICP-OES) (720-ES, Agilent) for Si, Al,

Fe, Mg, Ca, Na, and with an inferred absorption method after fusion (LECO TC-436Ar) under inert gas for O. The thermal conductometric method (LECO TC-436Ar) was used after fusion under inert gas for N and the infrared absorption method (LECO CS-844) was used after combustion for C. Fourier transform infrared (FTIR) spectra of alumina were recorded with a Nicolet iS50R (Thermo Scientific). Sixty-four scans were collected for each measurement in the spectral range of 400-4,000 cm^{-1} with a resolution of 4 cm^{-1} .

The size of the alumina sample used here was $3.0 \times 3.0 \times 0.3 \text{ cm}^2$ (Figure 1b). The measure specific surface area of the alumina via the BET was $1.5 \text{ cm}^2 \text{ mg}^{-1}$. The chemical composition of alumina was confirmed as 47.3% Al along with 1.44% Si, 0.03% Fe, 0.40% Mg, 0.02% Ca, 0.04% Na, 45% O, <1% N and 0.056% C using an ICP-OES for mass % chemical analysis. Figure 1c shows the XRD pattern of alumina in which characteristics peaks are attributed to the PDF card 10-0173 of α -alumina. Figure 1d shows an SEM image of alumina and Figure 1e provides a magnified view of Figure 1d. The SEM image reveals that the alumina is composed of high-density, interconnected micropores and the 50-200 μm pore diameter is optimal for infiltrating water. The SEM/EDX was also used to investigate the composition of alumina (Figure S1). The EDX spectrum (Figure S1b), indicates peaks of Al and O and Figures S1c-d present elemental mapping of Al and O.

FTIR spectra of alumina (Figure S2) show a dip with wavenumbers 3,310 attributed to the $-\text{OH}$ stretching mode and a dip at $1,737 \text{ cm}^{-1}$ that can be attributed to the bending mode⁴⁸. The dip at $1,074 \text{ cm}^{-1}$ corresponds to Al-O-H and bands at 628, and 482 cm^{-1} are attributed to Al-O bonds⁴⁹. Wettability and impregnation of water into the porous alumina were measured with a contact angle meter (DM700) and demonstrated (Figure S3) with a 1- μL water droplet placed on the alumina surface. Captured dynamic images of the droplet on the alumina illustrate a super hydrophilic surface. The inherently hydrophilic surface of alumina facilitates rapid flow of water through its pores, which greatly increases electricity generation driven by transpiration.

The alumina sample was connected with two electrodes and placed in a beaker to measure the potential drop across the alumina sample. The alumina sample was inserted vertically into a beaker filled with deionized (DI) water covering one half of the alumina (1.5 cm), and leaving the upper half exposed to the atmosphere. One electrode placed at the end of the sample was immersed in water. The height to which water infiltrated was significantly higher than the water level in the beaker, due to the capillary action of the micropores. Mimicking transpiration in plants, with evaporation of water at the alumina block surface, water in the container had to be quickly replenished, infiltrating into the alumina above the water level.

Results And Discussion

Although porous alumina is an insulating material, it can be converted into a surface conductor when in contact with water and yields a substantial amount of electrical power associated with surface evaporation. The DI water used here has an electrical conductivity of $0.055 \mu\text{S/cm}$, and the measured conductivity of completely wet alumina due to its water-dielectric charge interface was $1286.10 \mu\text{S/cm}$

(measured by zeta potential), orders of magnitude higher than that of pristine dry alumina (0.0001 $\mu\text{S}/\text{cm}$).

When the alumina block is partly soaked in water, voltage generation as high as 0.27 V was observed with high stability. The measured I-V curve exhibits a short circuit current of nearly 1.2 μA with an open-circuit voltage of 0.5 V. The alumina device shows good long-term stability (Figure 2a) and required about an hour before achieving a stable voltage (Figure S4). Evaporation-induced voltage of the alumina device achieved a stable output of nearly 0.27 V after about 1 h under ambient conditions. To further check the long-term stability of alumina, the measurement was continued for 7 days, showing the stability of generated voltage (Figure 2b). The I-V curves indicate that water-immersed alumina is conductive (Figure 2c). A completely dry sample before addition of water shows 0 μA (Figure 2c), as the resistivity is $\sim 10^{10}$ $\text{ohm}\cdot\text{cm}$. After immersion in water, the IV curve exhibits a slope with an offset indicating the power-generating nature of the water/alumina system (Figures 2c-d). Current versus time data is presented in Figure S5.

Maximum instantaneous output power density can be calculated²⁸ as $P_{\text{max}} = J_{\text{max}} \times V_{\text{max}}$, where J_{max} (1.2 μA) and V_{max} (0.27 V) are the maximum short-circuit current density and open-circuit voltage, respectively. The maximum instantaneous output power density was calculated as 0.324 ± 0.02 μW . The observed phenomena resemble the behaviour of so-called streaming potential observed with candle black soot and carbon nanotubes in contact with water. However, in those cases, voltage values are an order of magnitude less than the current results and their mechanical stability is very fragile, because the material adheres only weakly to the substrate. In contrast, the present system is a rigid solid medium, and yields far higher voltage than reported carbon-based materials. This is rather surprising, as the original material is an electrical insulator when dry, yet it yields substantial voltage when in contact with water. As a control experiment, we prepared a “carbon-coated” alumina using candle black soot (Figure S6) and other types of devices (Figure S7), and compared them with our pristine uncoated alumina. The result confirms that voltage generation is reduced significantly if the alumina surface is loaded with carbon, and other types of devices show far lower voltages as discussed in Note S1 and Note S2.

When the alumina was sealed within the beaker using a plastic wrapper (Figure S8), the induced voltage dropped, finally approaching to zero (Figure 3a). When the beaker was sealed to create a closed system, water vapor content in the air above the water surface became remarkably high and evaporation eventually stopped. Therefore, it is apparent that electricity generation ceased when the saturation deficit reached zero. Moreover, evaporation-induced voltage of the alumina could be inverted and maintained at the same height, by flipping the two electrodes (Figure 3b). When the device was inverted and the other end was immersed in water without changing the electrical connections, the voltage reversed its sign, but reached the same amplitude. These results indicate that water evaporation is the driving force for the electricity generation, and that the direction of the voltage is correlated with the direction of water flow driven by evaporation.

Further insights into voltage generation can be obtained from additional experiments using DI water with different immersed heights of the alumina sample in water. Maximum voltage was observed when the alumina was 1, 1.5 or 2 cm inserted into water (Figure 4a). Generated voltage was reduced after inserting the sample 0.5 or 2.5 cm into the water, where either electrode was at the water's surface. The voltage reduced further when the sample was completely out or completely in the water. Placing the air-water interface in the middle of the porous alumina sample was essential for voltage generation, which effectively promoted evapotranspiration through the porous media.

After that, the behaviour of the induced voltage was examined with water ejection and injection with a speed of 100 $\mu\text{L/S}$ and a 70° placement angle. A syringe pump was used (Figure 4b). The beaker was initially filled to 3 cm sample height, after few minutes when the water was gradually ejected from the beaker until 0.5 cm sample height, voltage quickly increased and reached maximum voltage (Figures 4b-c). Afterward, water was re-filled reaching near 3 cm sample height (yet partly exposed to the air) and voltage decreased to 0.18 V from 0.26 V. This behaviour was highly reproducible. When the voltage difference reached its maximum and remained stable, an equilibrium state was attained for flowing water molecules inside the alumina, i.e., when some water molecules outflow at one end the same number of water molecules entered the alumina from the other end. However, when the water was re-filled beyond 2.5 cm on the sample and immersed nearly completely, the equilibrium was disturbed due to a quick reduction of the air-alumina interface; therefore, the voltage dropped very quickly. Similar voltage behaviour was also observed for streaming potential in carbon nanotubes²³.

Next, streaming voltage performance was examined with faster water flow rates (250 and 500 $\mu\text{L/S}$) (Figures S9a-b). The results revealed that the voltage generation trend is similar with different water flow rates. Next, the influence of sample placement angle on voltage generation was investigated, keeping the sample height at 1.5 cm in water (Figure 4d). Maximum voltage was observed at a sample angle of 70°.

It should be noted that output performance of the alumina device can be easily scaled up with simple series or parallel connections. Two alumina samples were connected in series and in parallel (Figures 5a-b). When samples were connected in parallel, the voltage was the same as that of a single sample (Figure 2a); however, the current was nearly doubled during current measurements. When two alumina samples were connected in series and parallel, the corresponding open circuit voltage and short circuit values accorded with series and parallel circuit law (Figure 5b). Therefore, the alumina device can be boosted to any value by connecting device units in series and in parallel when more electricity is needed and can be used as a stable power source in electronic devices. On the other hand, by changing the alumina size we did not observe any significant difference in the induced voltage as discussed in Note S3 and shown in Figure S10.

Dependence of the generated voltage on the ionic concentration was also studied to examine whether the intrinsic properties of the liquid affect the performance of the water/ alumina interface. Three concentrations of NaCl, 0.01, 0.1 and 0.5 weight percentage (wt.%) were chosen to compare with DI water. All salt solutions produced much lower voltages than DI water (Figure 6a). The Debye length, which is the

distance for significant charge separation to occur, is inversely proportional to the square root of the ionic concentration^{50,51}. Above the critical molar concentration, an increase in the number of anions screens the polarization at the alumina/water interface, possibly redistributing the surface charge accumulated at the alumina/water interface. Therefore, the power generation capacity of the alumina device in the above three NaCl solutions changes significantly with salt concentration.

Next, the effect of illumination on voltage generation was investigated by illuminating the alumina block with high-intensity (800 mW/cm²) and standard (100 mW/cm²) simulated sunlight using a solar simulator. The voltage decreased as solar simulator irradiance increased (Figure 6b). During light illumination, alumina absorbed light and due to photothermal heating, the wet alumina surface dried partly, suppressing the amount of water moving upward.

Since the wetting of the alumina surface and water evaporation are essential to this power generation process, we further examined the effect of temperature. Figure 7 shows the voltage signals as the water temperature was varied from 1°C to 40°C in the beaker and sample placed in a temperature-controllable water bath. A larger electric signal was detected at higher temperatures (Figures 7 and S12). Since the rate of vaporization of water is higher at higher temperatures, water flow at the alumina interface is increased, enhancing power generation. These results suggest the utility of this method to produce electricity in warmer environments. Such alumina-based evaporation induced electricity generation opens a new way to convert waste heat into electricity. Since alumina is a rather stable and widely used industrial ceramic, this evaporation-induced energy harvesting can open a new field in ceramic research, utilizing porous materials for small-scale energy harvesting devices for circumglobal applications.

We further discuss the possible mechanism of evaporation-induced power generation at the alumina surface. First, the zeta potential of the alumina was measured to be -98.19 mV (Figure S13). The zeta potential gives an indication of the negative charge present on the alumina surface⁵² and this negative charge may be associated with surface -OH groups on the alumina surface, consistent with our FTIR measurements (Figure S2)^{48,49}. These -OH functional groups exhibit a high negative zeta potential on the surface and make the interior of the porous alumina super hydrophilic. Water molecules are attracted and wets on the hydroxylated alumina surface and then move upward through the porous channels via capillary action and eventually evaporate (Figure 8). Protons (H⁺), or hydronium ions (H₃O⁺) accumulate along the alumina surface and form a polarized surface layer known as the electric double layer (EDL), attracted by the negative surface charge. The thickness of the EDL is relatively large (several hundreds of nanometers) due to the large Debye screening length of pure water. In this EDL region, a substantial numbers of protons are attracted to the water alumina interface, then a deficiency of protons in the channel centers need to be compensated by additional water self-ionization, which subsequently boosts the conductivity of the entire system^{53,54}. These ions in the pore-confined water freely flows upward along the channel due to transpiration. Contrarily, protons trapped directly on the surface or captured in the interfacial water network adsorbed on the surface can hop or move moderately via a Grotthuss mechanism^{55,56}. Accordingly, these ions migrate uphill together with water under a capillary force as

water evaporates from the alumina, thus the above-described interfacial charges (positive and negative) are also dragged simultaneously in the same direction. Since their distribution near the surface region are different, positive net current will be generated due to the possibility of different diffusion speeds for two components. Then the two electrodes attached to the upper and lower sides can monitor the spontaneous voltage generation across the entire alumina sample. Together with this flow charge dynamics in transpiring water, other possible causes like chemical potential difference of the top and the bottom electrodes may arise from the difference in their environments (air versus water). Since the alumina/electrode systems is symmetric in its geometry, voltage generation across this symmetric device must be either originated from the uniaxial movement of water or the amount of oxygen in contact to the two electrodes. This can contribute to the reduction of stainless clamp, which seems minor contribution as the change in pH value of water was minute (~ 0.8) even after one week of continuous measurement.

Conclusion

We have demonstrated an extremely simple method of electricity generation that offers applications in energy harvesting. Microporous alumina generated electricity from water evaporation through its micropores due to dragging of carriers at the water-alumina interface. The microporous alumina was highly hydrophilic and contains numerous pores with a large specific surface area that contributes to rapid water flow and formation of near-surface carriers. Evaporation-driven water flow within porous alumina membranes could generate stable voltage up to 0.27 V under ambient conditions. Our results show that power generated using alumina can be increased by elevating the water temperature. The current results inspire us to apply inexpensive alumina to produce electricity in warm, dry environments. The significance of this work is that porous alumina not only offers an inexpensive and efficient small-scale power generator, but also opens a new way to harvest energy by water transpiration, which should be feasible to any place and any time on earth as long as there is water.

Declarations

AUTHOR INFORMATION

Corresponding Author

sishii@nims.go.jp MANPREET.Kaur@nims.go.jp (Manpreet Kaur)

NAGAO.Tadaaki@nims.go.jp (Tadaaki Nagao)

Funding Sources

This work was supported by JSPS KAKENHI (16H06364) and CREST “Phase Interface Science for Highly Efficient Energy Utilization” (JPMJCR13C3) from the Japan Science and Technology Agency.

Acknowledgements

We thank Dr. Taro Takemura and Ms. Li Xianglan at the Molecules and Materials Synthesis Platform, NIMS, for performing zeta potential measurements. We would also like to show our gratitude to Dr. Akio Iwanade for his assistance in ICP- OES analysis.

Author Contributions

The manuscript was written with contributions from all authors. All authors have approved the final version of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supporting Information. Figures S1-S13.

References

- 1 Omer, A. M. Green energies and the environment. *Renew. Sust. Energ. Rev.* **12**, 1789-1821 (2008).
- 2 Okkerse, C. & Van Bekkum, H. From fossil to green. *Green Chem.* **1**, 107-114 (1999).
- 3 Ellabban, O., Abu-Rub, H. & Blaabjerg, F. Renewable energy resources: Current status, future prospects and their enabling technology. *Renew. Sust. Energ. Rev.* **39**, 748-764 (2014).
- 4 Hovel, H. J. Solar cells. *NASA STI/Recon Technical Report A* **76** (1975).
- 5 Brabec, C. J., Sariciftci, N. S. & Hummelen, J. C. Plastic solar cells. *Adv. Funct. Mater.* **11**, 15-26 (2001).
- 6 Lin, S. *et al.* Tellurium as a high-performance elemental thermoelectric. *Nat. Commun.* **7**, 10287 (2016).
- 7 Khan, Z. U. *et al.* Thermoelectric polymers and their elastic aerogels. *Adv. Mater.* **28**, 4556-4562 (2016).
- 8 Katsouras, I. *et al.* The negative piezoelectric effect of the ferroelectric polymer poly (vinylidene fluoride). *Nat. Mater.* **15**, 78 (2016).
- 9 Zi, Y. *et al.* Effective energy storage from a triboelectric nanogenerator. *Nat. Commun.* **7**, 10987 (2016).
- 10 Ahuja, D. & Tatsutani, M. Sustainable energy for developing countries. *SAPI EN. S. Surveys and Perspectives Integrating Environment and Society* (2009).

- 11 Yang, R., Qin, Y., Dai, L. & Wang, Z. L. Power generation with laterally packaged piezoelectric fine wires. *Nat. Nanotechnol.* **4**, 34 (2009).
- 12 Grätzel, M. Photoelectrochemical cells. *Nature* **414**, 338-344 (2001).
- 13 Wang, X., Song, J., Liu, J. & Wang, Z. L. Direct-current nanogenerator driven by ultrasonic waves. *Science* **316**, 102-105 (2007).
- 14 Bagher, A. M., Vahid, M., Mohsen, M. & Parvin, D. Hydroelectric energy advantages and disadvantages. *American Journ. of Energ. Sci.* **2**, 17-20 (2015).
- 15 Feng, J. *et al.* Single-layer MoS₂ nanopores as nanopower generators. *Nature* **536**, 197 (2016).
- 16 Osterle, J. A unified treatment of the thermodynamics of steady-state energy conversion. *Appl. Sci. Res., Sec. A* **12**, 425-434 (1964).
- 17 Burgreen, D. & Nakache, F. Efficiency of pumping and power generation in ultrafine electrokinetic systems. *J. Appl. Mech.* **32**, 675-679 (1965).
- 18 Yang, J., Lu, F., Kostiuik, L. W. & Kwok, D. Y. Electrokinetic microchannel battery by means of electrokinetic and microfluidic phenomena. *J. Micromech. Microeng.* **13**, 963 (2003).
- 19 Guo, W. *et al.* Bioinspired two dimensional nanofluidic generators based on a layered graphene hydrogel membrane. *Adv. Mater.* **25**, 6064-6068 (2013).
- 20 Xue, G. *et al.* Water-evaporation-induced electricity with nanostructured carbon materials. *Nat. Nanotechnol.* **12**, 317 (2017).
- 21 Ding, T. *et al.* All printed porous carbon film for electricity generation from evaporation driven water flow. *Adv. Funct. Mater.* **27**, 1700551 (2017).
- 22 Ho Lee, S., Kim, D., Kim, S. & Han, C. S. Flow induced voltage generation in high-purity metallic and semiconducting carbon nanotubes. *Appl. Phys. Lett.* **99**, 104103 (2011).
- 23 Zhao, Y. *et al.* Individual water filled single walled carbon nanotubes as hydroelectric power converters. *Adv. Mater.* **20**, 1772-1776 (2008).
- 24 Král, P. & Shapiro, M. Nanotube electron drag in flowing liquids. *Phys. Rev. Lett.* **86**, 131 (2001).
- 25 Ghosh, S., Sood, A. & Kumar, N. Carbon nanotube flow sensors. *Science* **299**, 1042-1044 (2003).
- 26 Ghosh, S., Sood, A., Ramaswamy, S. & Kumar, N. Flow induced voltage and current generation in carbon nanotubes. *Phys. Rev. B* **70**, 205423 (2004).

- 27 Zhao, F., Cheng, H., Zhang, Z., Jiang, L. & Qu, L. Direct power generation from a graphene oxide film under moisture. *Adv. Mater.* **27**, 4351-4357 (2015).
- 28 Zhao, F., Liang, Y., Cheng, H., Jiang, L. & Qu, L. Highly efficient moisture-enabled electricity generation from graphene oxide frameworks. *Energy Environ. Sci.* **9**, 912-916 (2016).
- 29 Yin, J. *et al.* Generating electricity by moving a droplet of ionic liquid along graphene. *Nat. Nanotechnol.* **9**, 378-383 (2014).
- 30 Yin, J. *et al.* Waving potential in graphene. *Nat. Commun.* **5**, 3582 (2014).
- 31 Ji, B. *et al.* Intelligent multiple-liquid evaporation power generation platform using distinctive Jaboticaba like carbon nanosphere@TiO₂ nanowires. *J. Mater. Chem. A* **7**, 6766-6772 (2019).
- 32 Lu, Y. *et al.* A Filter Paper-Based Nanogenerator via Water Drop Flow. *Adv. Sustainable Sys.* 1900012 (2019).
- 33 Gao, X. *et al.* Electric power generation using paper materials. *J. Mater. Chem. A* **7**, 20574-20578 (2019).
- 34 Okada, T. *et al.* Nitrogen doping effect on flow induced voltage generation from graphene-water interface. *Appl. Phys. Lett.* **112**, 023902 (2018).
- 35 Yang, P. *et al.* Solar-driven simultaneous steam production and electricity generation from salinity. *Energy Environ. Sci.* **10**, 1923-1927 (2017).
- 36 Zhou, X. *et al.* Harvesting Electricity from Water Evaporation through Microchannels of Natural Wood. *ACS Appl. Mater. Interfaces* **12**, 11232-11239 (2020).
- 37 Shao, C. *et al.* Large-Scale Production of Flexible, High-Voltage Hydroelectric Films Based on Solid Oxides. *ACS Appl. Mater. Interfaces* **11**, 30927-30935 (2019).
- 38 Yoon, S. G. *et al.* Natural Evaporation-Driven Ionovoltaic Electricity Generation. *ACS Appl. Electronic Mater.* **1**, 1746-1751 (2019).
- 39 Routkevitch, D., Bigioni, T., Moskovits, M. & Xu, J. M. Electrochemical fabrication of CdS nanowire arrays in porous anodic aluminum oxide templates. *J. Phys. Chem.* **100**, 14037-14047 (1996).
- 40 Huang, K. *et al.* Asymmetric light reflectance effect in AAO on glass. *Opt. express* **19**, 1301-1309 (2011).
- 41 Yanagishita, T., Kondo, T., Nishio, K. & Masuda, H. Optimization of antireflection structures of polymer based on nanoimprinting using anodic porous alumina. *J. Vac. Sci. Technol. B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena* **26**, 1856-1859 (2008).

- 42 Kanamori, Y., Hane, K., Sai, H. & Yugami, H. 100 nm period silicon antireflection structures fabricated using a porous alumina membrane mask. *Appl. Phys. Lett.* **78**, 142-143 (2001).
- 43 Kant, K., Yu, J., Priest, C., Shapter, J. G. & Losic, D. Impedance nanopore biosensor: influence of pore dimensions on biosensing performance. *Analyst* **139**, 1134-1140 (2014).
- 44 Kaur, M., Ishii, S., Shinde, S. L. & Nagao, T. All Ceramic Solar Driven Water Purifier Based on Anodized Aluminum Oxide and Plasmonic Titanium Nitride. *Adv. Sustain. Sys.* **3**, 1800112 (2019).
- 45 Farhat, M. *et al.* Mirror-backed dark alumina: a nearly perfect absorber for thermoelectronics and thermophotovoltaics. *Sci. Rep.* **6**, 19984 (2016).
- 46 Dao, T. D. *et al.* Infrared perfect absorbers fabricated by colloidal mask etching of Al–Al₂O₃–Al trilayers. *ACS Photonics* **2**, 964-970 (2015).
- 47 Yokoyama, T. *et al.* Spectrally Selective Mid-Infrared Thermal Emission from Molybdenum Plasmonic Metamaterial Operated up to 1000 °C. *Adv. Opt. Mater.* **4**, 1987-1992 (2016).
- 48 El-Naggar, A. Y. Characterization of modified and polymer coated alumina surfaces by infrared spectroscopy. *J. Spectrosc.* **2013** (2013).
- 49 Liu, C., Shih, K., Gao, Y., Li, F. & Wei, L. Dechlorinating transformation of propachlor through nucleophilic substitution by dithionite on the surface of alumina. *J. Soils Sediments* **12**, 724-733 (2012).
- 50 Duffin, A. M. & Saykally, R. J. Electrokinetic hydrogen generation from liquid water microjets. *J. Phys. Chem. Lett.* **111**, 12031-12037 (2007).
- 51 Zhang, L. & Chen, X. Nanofluidics for giant power harvesting. *Angew. Chem. Int. Ed.* **52**, 7640-7641 (2013).
- 52 Das, M. R., Borah, J. M., Kunz, W., Ninham, B. W. & Mahiuddin, S. Ion specificity of the zeta potential of α -alumina, and of the adsorption of p-hydroxybenzoate at the α alumina water interface. *J. Colloid Interface Sci.* **344**, 482-491 (2010).
- 53 Arrhenius, S. On the dissociation of substances dissolved in water. *Z. Phys. Chem* **1**, 631 (1887).
- 54 Heyrovská, R. Ionic concentrations and hydration numbers of “supporting electrolytes”. *Electroanal.: An International Journal Devoted to Fundamental and Practical Aspects of Electroanalysis* **18**, 351-361 (2006).
- 55 Xu, T. *et al.* Electric power generation through the direct interaction of pristine graphene-oxide with water molecules. *Small* **14**, 1704473 (2018).
- 56 Karim, M. R. *et al.* Graphene oxide nanosheet with high proton conductivity. *J. Amer. Chem. Soc.* **135**, 8097-8100 (2013).

Figures

Figure 1

(a) Schematic diagram of the experimental setup and a photograph of the device. (b) Photograph of the porous alumina block. (c) XRD pattern (black curve) of the alumina and a pattern from the PDF card (10-0173) (red). (d) SEM image of alumina. (e) Magnified view of (d).

Figure 2

(a) Voltage generated by alumina with respect to time when alumina was immersed 1.5 cm into water. (b) Voltage generated by alumina continuously for 7 days, in which each cycle represents 10 hours of measurements per day. (c) An I-V curve with the dry sample without water and wet sample half-immersed in water. (d) Magnified I-V curve near the origin shown in (c).

Figure 3

(a) Voltage signal in open and closed system with schematic representations. (b) Effect of electrodes interchange on induced voltage with sample setup schematics.

Figure 4

Voltage generation performance of alumina with (a) different sample heights inserted into the water, where the key shows different degrees (cm) of sample immersion in water and the inset schematic presents the amount of sample immersion in water at 70°. (b) Schematic representation of sample height (cm) in the water. (c) Dependence of the induced voltage difference on water transpiration speed. (d) Different sample placement angle at 1.5 cm sample height in water.

Figure 5

(a) Voltage and (b) Current generated by two-alumina samples in series and parallel connections.

Figure 6

(a) Voltage generation in relation to (a) NaCl concentration and (b) simulated sunlight intensity.

Figure 7

(a) Evaporation-induced voltage plotted as a function of temperature; (b) Schematic representation of water transpiration through alumina.

Figure 8

Schematic diagram of evaporative power generation.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupportingInfo.docx](#)
- [TableofContentsGraphic.pdf](#)