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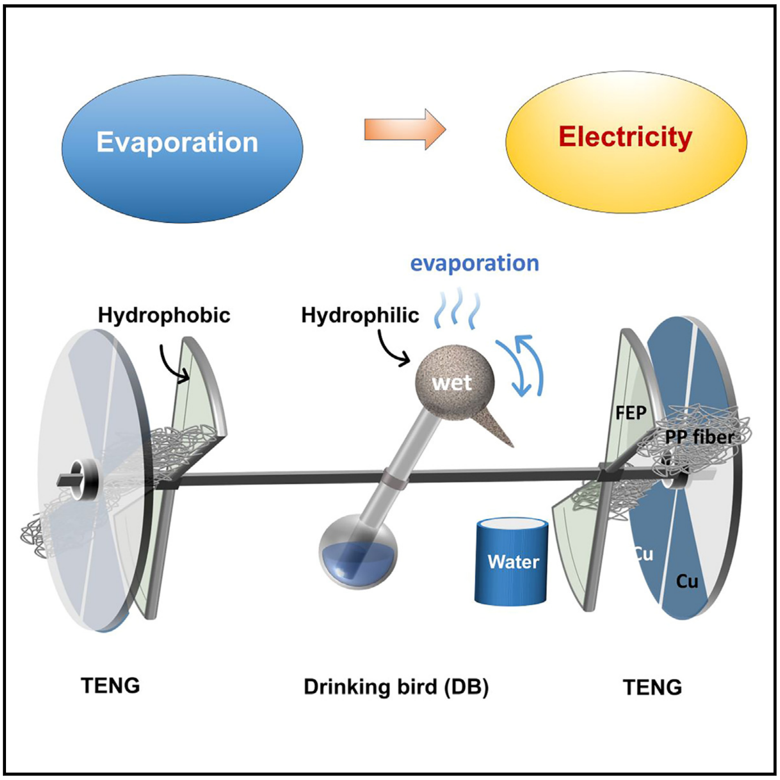
Drinking-bird-enabled triboelectric hydrovoltaic generator

Graphical abstract



Highlights

- An evaporation energy harvester leveraging triboelectric effect was proposed
- A "drinking bird" engine converts evaporation energy into kinetic motion
- A triboelectric nanogenerator converts kinetic motion into electricity
- The device generates over 100 V voltage through natural water evaporation

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In brief

Water evaporation captures half of Earth's surface solar energy, presenting a substantial renewable energy opportunity. This study reports a strategy to harness evaporation energy using water latent heat and the triboelectric effect. Inspired by the drinking bird toy, a natural evaporation-driven heat engine converts evaporation's latent heat into slow-frequency motion, which is then converted into electricity by using a low-friction triboelectric nanogenerator. The proposed drinking bird triboelectric hydrovoltaic generator (DB-THG) generates over 100 V voltage from water evaporation in the ambient environment.

Develop
Prototype with demonstrated applications in relevant environment

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Drinking-bird-enabled triboelectric hydrovoltaic generator

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THE BIGGER PICTURE Water evaporation is a promising source of clean energy due to its significant energy transfer. Various hydrovoltaic methods have been proposed to convert evaporation energy into electricity. However, these methods heavily rely on the streaming potential generated by ions flowing near nanomaterials. The limited space for ion-material interaction and underutilization of bulk water lead to low energy conversion efficiency. This study introduces an innovative method for harvesting evaporation energy by leveraging the latent heat of water evaporation and the triboelectric effect. The proposed device combines a "drinking bird" engine and a triboelectric nanogenerator to convert evaporation into kinetic motion, which is then used to generate electricity. By harnessing natural water evaporation, an output voltage exceeding 100 V has been achieved. This research provides a practical method for powering small electronic devices using evaporation energy.

SUMMARY

The evaporation process involves the most significant amount of energy transfer on Earth. Various hydrovoltaic techniques have been proposed to convert evaporation energy into electricity, but they mainly rely on streaming potential that suffers from the limitations of low voltage output. Herein, we report an alternative strategy for harvesting evaporation energy by using water latent heat and the triboelectric effect. We use a natural, evaporation-driven heat engine inspired by a drinking bird toy to convert the latent heat of evaporation into slow-frequency motion and then convert the mechanical energy into electricity via a specialized triboelectric nanogenerator featuring low friction drag. Our drinking-bird triboelectric hydrovoltaic generator (DB-THG) generates >100 V voltage from water evaporation in the natural environment. Using the prototype of DB-THG, we power small electronics such as 20 liquid crystal displays, temperature sensors, and calculators in ambient conditions using water as fuel.

INTRODUCTION

As early as around 400 BC, humans began to use the natural flow of moving water in rivers or streams and convert it into useful mechanical energy. In the late 19th century, flowing water was used to generate electricity through electromagnetic generators, which is still the dominant hydropower technology today.[1] Apart from the conventional flowing water utilization, one largely unexplored water energy source is evaporation, which consumes an average energy flux of $\sim$88 ± 10 W m^{-2}, about 50% of the solar energy absorbed by the Earth's surface, offering promise as a new green energy source.[2] Over the past several years, hydrovoltaic technologies that eliminate the requirement of bulky equipment emerged, which successfully harnessed evaporation energy in the form of bulk water, waves, raindrops, and moisture.[1,3–19] Notably, spore-based hydrovoltaic generators were developed in 2014 to generate about 1–3 V by leveraging the evaporation-induced deformation in spore materials and the electromagnetic effect.[4,5] In 2017, a voltage up to 4.8 V could be achieved based on flow potential using porous carbon nanomaterials through multiple devices in series.[10] The voltage output of such a hydrovoltaic generator can be further improved by material modification or varying the operation conditions[8,20] (Figure 1A).

Despite extensive progress, a host of daunting challenges lie ahead. First, the direct evaporation-to-electricity generation

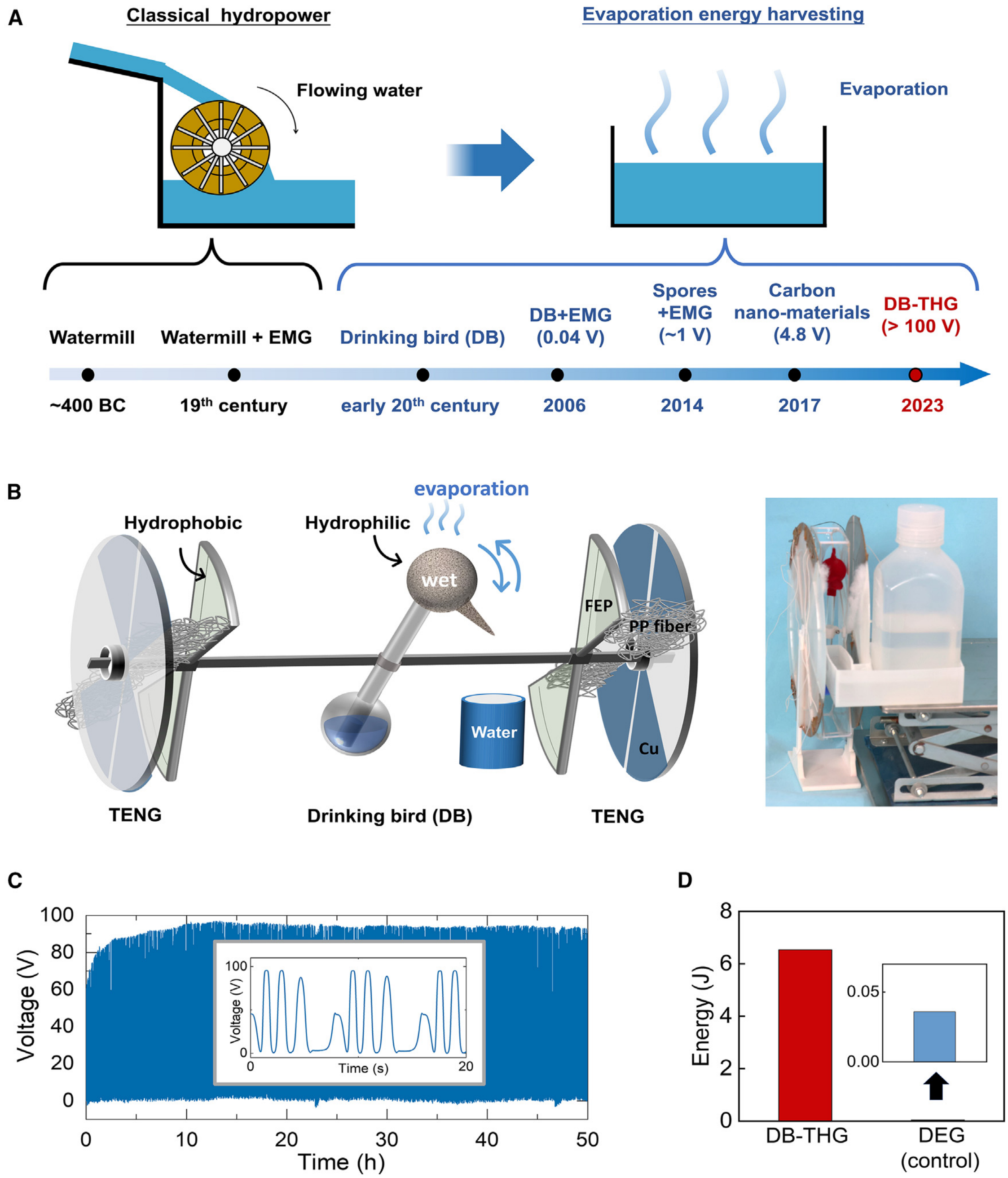

Figure 1. Design and electrical output of the drinking bird triboelectric hydrovoltaic generator (DB-THG)
(A) Timeline of the development of classical hydropower and the modern evaporation energy harvesting technology.
(B) Illustration and photograph of DB-THG.
(C) A continuous recording of the voltage output from the DB-THG for 50 h. About 100 mL water has been consumed during 50 h of operation of the DB-THG. Inset is the detailed voltage output for 20 s.
(D) Electric energy generated by 1 L water using DB-THG compared with that generated by droplet-based electricity generator (DEG).

originates from the streaming potential, which is generated as a collective ion flow within a short Debye length adjacent to nanomaterials, which are normally hydrophilic for preferential amplified water-solid interaction.[10,20] The striking contrast between the limited spatial area for effective ion-materials interaction and largely untapped bulky water leads to a relatively low energy conversion efficiency. The evaporation-to-electricity generation can be indirectly achieved by first transforming the liquid evaporation into the motion of materials or devices, as in the case of spore.[5] However, such a motion is low frequency and thereby is ineffective for highly efficient electromagnetic induction that typically demands a high-frequency motion. In both approaches, these functional materials, normally hydrophilic, suffer from material degradation and relatively low durability owing to their direct contact with water. On the other hand, the water-solid-based triboelectric nanogenerator (TENG) offers the potential to convert the low-frequency and random mechanical motions of water into electricity by taking advantage of hydrophobic materials with high surface charge density. Yet, the two have never crossed paths, owing to their conflicting requirements for material properties, especially surface wettability.

To address these challenges, we propose a new strategy that allows for harnessing the latent heat of water evaporation and simultaneously eliminates the direct contact between water and functional materials. Our design in harnessing the latent heat of water evaporation was inspired by the drinking bird toy that is capable of continuously collecting the evaporation energy and converting it into low-frequency kinetic energy in the form of a swinging motion,[21–26] a classical invention dating back to the early 20th century[27–29] (Figures S1–S3). Moreover, to enhance the energy conversion efficiency from the low-frequency swing motion generated by the drinking bird engine, we design a TENG featuring patterned soft polypropylene (PP) cotton, which greatly reduces the friction loss between the tribo-materials, enabling the continual energy harvesting from the small mechanical energy induced by the evaporation. Our drinking bird triboelectric hydrovoltaic generator (DB-THG) achieves a voltage output of up to 100 V through water evaporation in the natural environment, significantly exceeding the previous study (Figure 1A).

RESULTS

The construction of the DB-THG is shown in Figures 1B and S4–S11. Our DB-THG contains a drinking bird engine and two TENG modules placed at both sides of the drinking bird. The drinking bird engine was reconstructed from a commercial drinking bird toy, which spontaneously dips the water in the front container without stopping, exhibiting an elusive feature of perpetual motion machines.[21–23,25] The main body of the drinking bird is a fully enclosed container consisting of two spherical glass bulbs connected by a small glass tube. One end of the tube is inserted into the lower bulb, called the "body," and filled with liquid of a boiling temperature of $\sim$40°C. The top bulb, known as the "head," is attached to a "beak" that is covered by absorbent cloth. The drinking bird oscillates around a rod placed on a stand produced by 3D printing technology. In front of the drinking bird, there is a tank filled with water. The tank can either be an open reservoir or a partially closed container. The latter option allows for a more efficient use of water due to a smaller water-air interface area (Figure S8). On each side of the drinking bird, there is a TENG power generation module equipped with patterned soft PP cotton. The two TENG modules are connected in parallel. Each TENG consists of a rotor and a stator. The rotors, along with two fan-shaped fluorinated ethylene propylene (FEP) films, swing with the bird's motion (Video S1). The stators are equipped with several fan-shaped copper sheets that connect to the external circuit (for details of the external circuit, refer to Figure S12). Two pieces of artificial cotton made of PP fibers are placed on the stator as tribo-materials.

With such a DB-THG, we achieve sustainable power generation from natural water evaporation. Figure 1C shows the voltage generation of a DB-THG continually running for 50 h at 24°C and 20% ± 5% relative humidity (RH) atmosphere. Over a period of 50 h, the drinking bird generated a maximum electrical energy of approximately 0.65 J from around 100 mL water, corresponding to 6.5 J per liter of water, which is about 180 times higher compared to the state-of-the-art droplet-based electricity generator[30] using the same amount of water (Figures 1D and S13–S17). Based on this test, the DB-THG shows an average power generation of approximately 3.6 μW. A comparison of the electric output of the DB-THG and other evaporation energy harvesters is shown in Table S1.

To illustrate the working principle of the DB-THG, we first focus on the kinetic motion generation process of the drinking bird engine (Figures 2 and S18). Simultaneously recording the motion of the drinking bird and the temperature distribution over the whole device, we observed that the temperature of the bird's head was always $\sim$3°C lower than that of the bird's body, which can be attributed to the evaporation process of the wet cloth covering the bird's head (Figures 2A, S19, and S20; Videos S2 and S3). The small temperature difference creates a pressure gradient inside the drinking bird, which serves as the driving force for its kinetic motions. The mechanism of the kinetic motion generation process is shown in Figure 2B. In the beginning, the bird starts off in an upright position with the internal fluid stored in the bottom glass bulb. Subsequently, due to the low temperature of the bird's head, the vapor in the bird's head condenses, and the pressure inside drops. This pressure difference between the head and body prompts the internal liquid to rise toward the bird's head. As the liquid ascends, the bird's center of mass shifts upward, causing the head to become heavier. Consequently, the bird's head moves forward and submerges into the water. During this dipping phase, the lower end of the tube emerges above the internal liquid, resulting in a complete connection between the chambers in the bird's head and body. The liquid then flows back to the bird's body, allowing the drinking bird to return to its original upright position. Before the bird takes its next dip, it will continue to swing several times. With the ongoing evaporation in its head, the drinking bird keeps dipping and swinging incessantly.

The appealing feature of our DB-THG lies in an efficient conversion of the small kinetic energy into electricity. The existing drinking-bird-based electromagnetic electricity generation technique suffers from low power output due to its low-frequency and weak kinetic motions, as evidenced by the previous experimental result that only 0.04 V of peak voltage and $\sim$3 μW of peak power were generated by leveraging the conventional generator[22] (Figure S21). In order to efficiently harness slow and weak kinetic motions, we employ the advanced TENG technique, which demonstrates outstanding capability in capturing low-frequency and small-scale kinetic energy.[31–33] To overcome the friction caused by tribo-materials in conventional TENGs, which restricts the movement of the drinking bird, we have made improvements to the TENG device. By utilizing patterned PP cotton as tribo-materials, we enable the device to operate

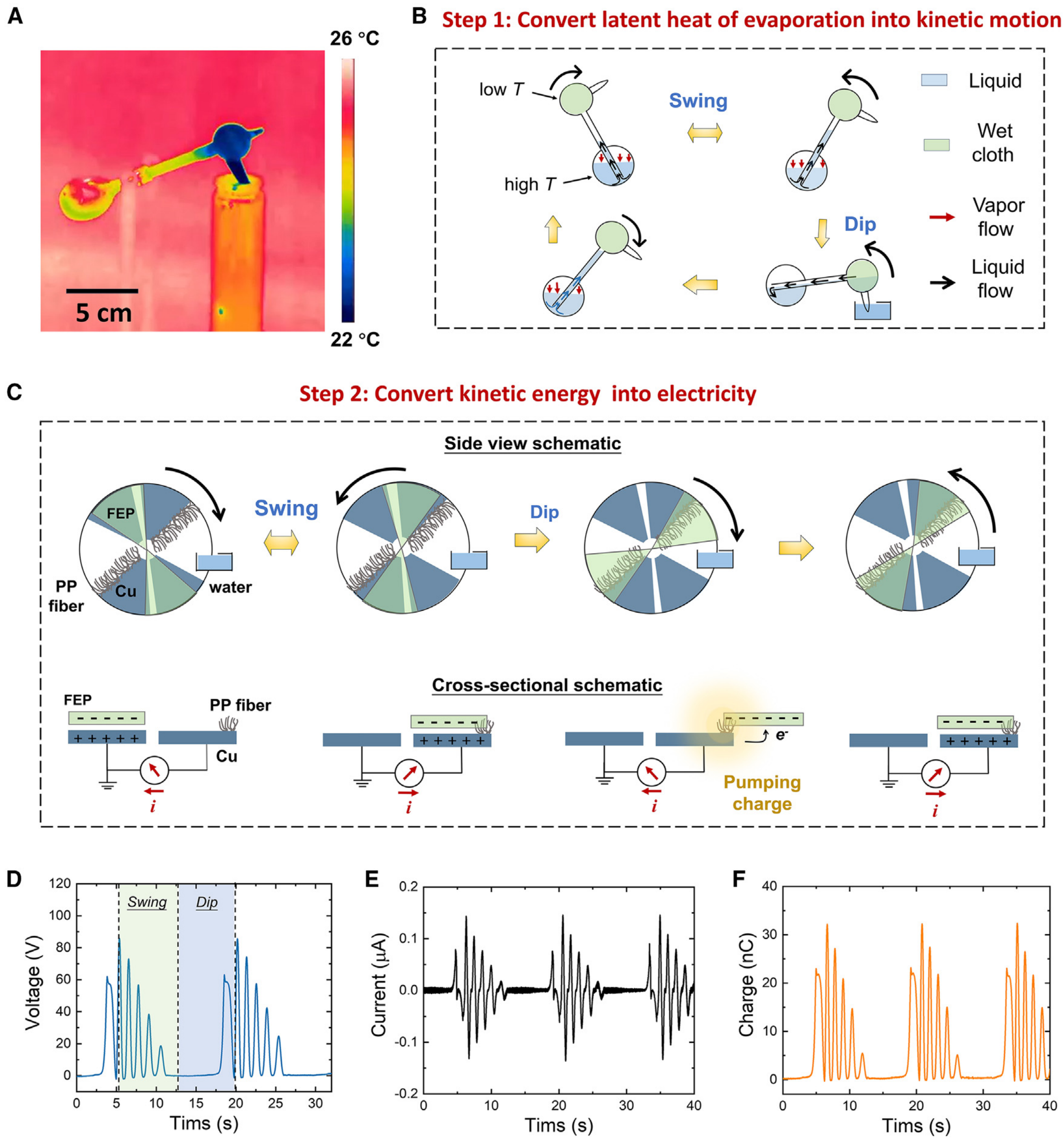

Figure 2. Working mechanism of the DB-DHG

(A) Temperature distribution of the DB-DHG as measured using a thermal camera, showing that the temperature of the bird's head is always ∼3°C lower than that of the bird's body.

(B) Illustration of the working mechanism of the drinking bird engine, showing the drinking bird moving, driven by the pressure difference inside the bird body that was induced by the temperature difference between the bird's head and body.

(C) Illustration of the working mechanism of the TENG module, showing the charge transfer between the two electrodes that forms an electric current.

(D–F) Voltage, current, and charge outputs of the DB-THG (temperature: 24°C, humidity: 28%).

in a soft-contact mode with intermittent intervals. Figure 2C demonstrates the mechanism of the electricity generation process of the TENG modules. For each TENG, the rotor, equipped with a FEP film, remains approximately 1 cm away from the stator to ensure minimal friction throughout the swinging process. As the rotor swings, the charged FEP film induces a transfer of counter-charges between the two Cu film electrodes on the stator, creating an electric current flow to power the load. Additionally, during the dipping stage, the FEP films connect with the patterned PP cotton located at the edge of the Cu electrodes, which facilitates the accumulation of negative charges onto the FEP film due to the triboelectrification effect. The generated voltage, current, and charge of the DB-THG depending on time are shown in Figures 2D–2F. It is worth noting that most electricity is generated during the swinging stage with zero friction loss, which significantly enhances energy conversion efficiency.

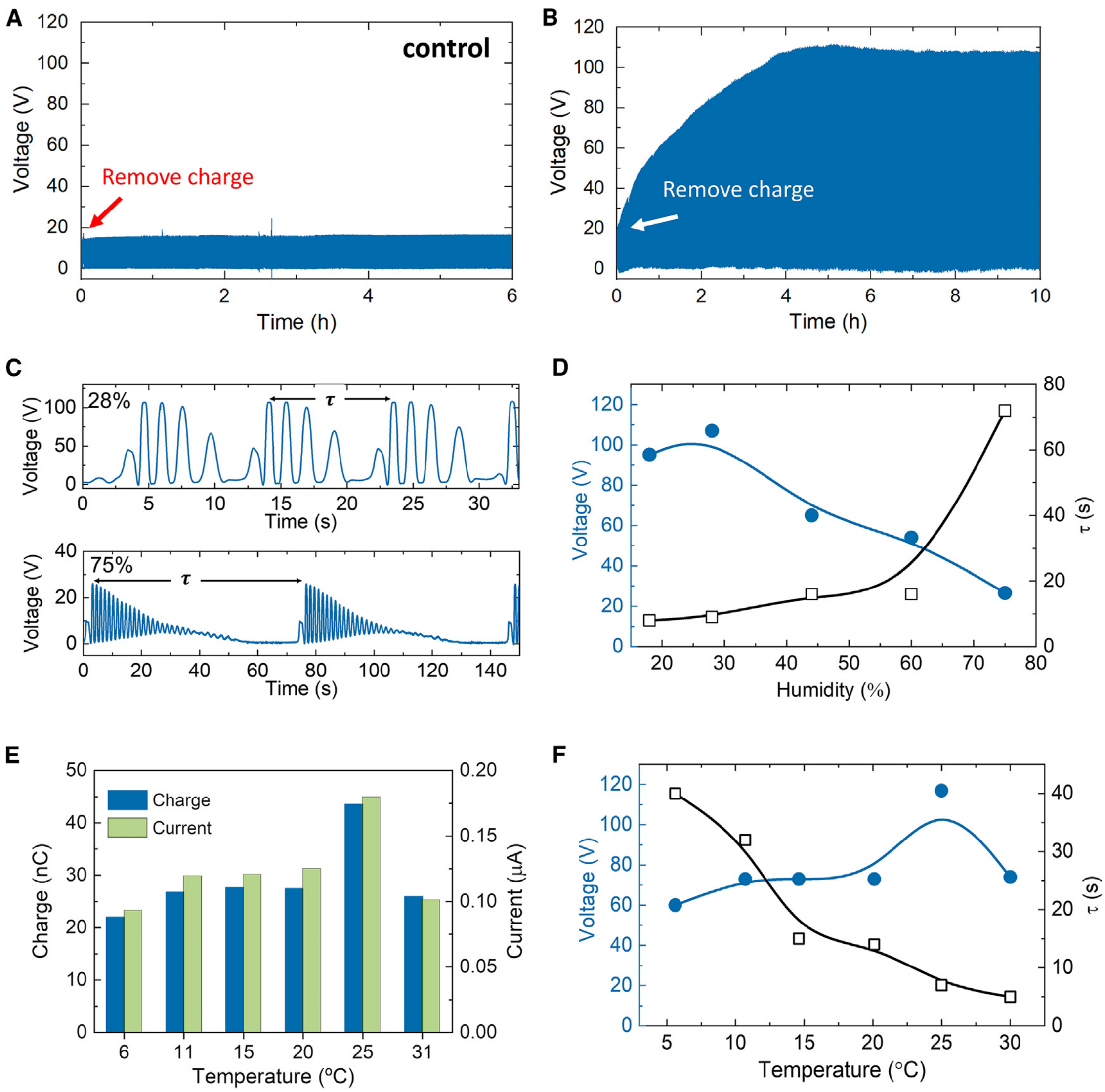

Figure 3. Performance of the DB-THG

(A and B) The performance recovery capability of the control device, with TENG operating in non-contact mode (A) and the DB-THG (B) demonstrating that once the surface charge of the FEP is eliminated, the functionality of the DB-THG can be restored during operation.

(C) The measured voltage outputs of the DB-THG in humidity of 28% and 75% (temperature of 24°C).

(D) The measured peak voltage and the cycle time τ of the DB-THG depending on humidity (keep constant temperature of 24°C), indicating the voltage output decreases with the humidity increase.

(E) The measured maximum charge and current output of the DB-THG depending on the temperature (keep constant humidity of 20% ± 5%). The charge and current output show fluctuations with changing temperatures.

(F) The measured peak voltage and the cycle time τ of the DB-THG depending on temperature (keep constant humidity of 20% ± 5%). The voltage output shows fluctuations with changing temperatures.

To demonstrate the functional sustainability of our design, we conducted a comparison between our DB-THG and a control device utilizing the conventional non-contact mode TENG[34] (Figure S22). To eliminate surface charges on the FEP films of both devices, an ion fan was employed (Figure S23). Notably, while the output of the control device remained consistently low, our DB-THG displayed an increase in output as a result of interval contact electrification between the FEP film and the PP cotton (Figures 3A and 3B). It is worth mentioning that the output of the conventional non-contact TENG could initially be high due to intentional charge injection or unintentional contact on the FEP film. However, the surface charges of the control device depleted rapidly and could not recover after degradation (Figure S24).

We then investigate the impacts of temperature and humidity on the performance of the DB-THG. To ensure reliable testing data, we initially operate the DB-THE for approximately 20 h to establish a stable surface charge. Subsequently, we conduct

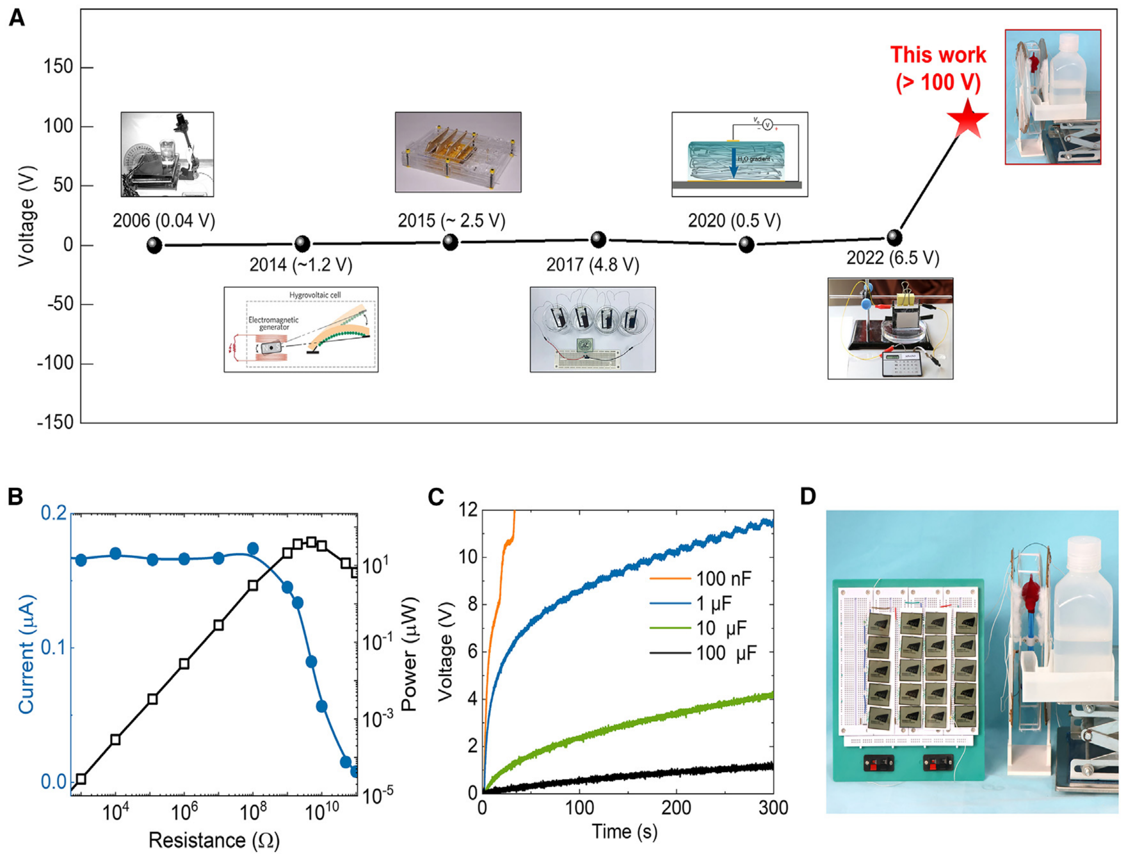

Figure 4. Demonstration of the DB-THG

(A) Comparison of the maximum voltage output of the DB-THG (this work) and that of the evaporation energy harvesting technology in other reports.

(B) The measured peak current and power depending on load resistance generated by a DB-THG (temperature: 25°C, humidity: 20%). The peak power output is ~40 μW with a load resistance of 5 MΩ.

(C) Capacitor charging performance of the DB-THG (temperature: 26°C, humidity: 30%).

(D) Photograph of directly powering 20 LCDs (26 × 31 mm) by DB-THG in ambient condition.

electrical output tests on the DB-THG (Figures S25–S37). Our findings indicate a decrease in electric output with increasing ambient humidity (Figures 3C, 3D, and S25–S30), which can be attributed to two factors. Firstly, in a humid environment, the motion of the drinking bird slows down due to reduced evaporation rates. Consequently, there is an increase in the cycle time τ, as illustrated in Figure 3C. This leads to a decrease in the contact frequency between the FEP and the PP cotton, resulting in hindered charge transfer onto the FEP film during the triboelectrification process. Consequently, the electric output experiences a significant reduction. Secondly, it is known from previous studies[35,36] that the contact electrification effect inherently weakens under high humidity conditions, further contributing to the observed low electric output. On the other hand, the electric output of the DB-THG exhibits fluctuations and attains its maximum value at 25°C in response to temperature variations (Figure 3E, 3F, and S31–S37). The interplay between the decrease in surface charge caused by high temperature and the rise in charge due to increased contact frequency may be the cause of this phenomenon. At elevated temperatures, the drinking bird experiences rapid oscillations due to enhanced evaporation rates, leading to an amplified charge pumping rate on the FEP film and, subsequently, a higher electric output. However, simultaneously, the charge on the FEP film tends to dissipate from the surface at high temperatures. While it is widely observed that increasing the temperature reduces surface charge density and enhances the dissipation of surface charge, the underlying mechanism is still debatable. This phenomenon may be attributed to either the thermionic emission effect[37,38] or the dissipation of surface charge alongside water molecules evaporation at higher temperatures,[39] requiring further investigation.

Our DB-THG achieved remarkable outputs, with maximum voltage, current, and charge reaching 107 V, 0.24 μA, and 40 nC, respectively (at 24°C, ~28% RH). These values far surpass those previously reported for water evaporation power generation,[4,5,10,20,22,40] as shown in Figure 4A. Moreover, our DB-THG not only excels in voltage generation but also delivers impressive power output. In an environment with a temperature of 25°C and a RH of ~20%, it generates a maximum peak power of ∼40 μW (Figure 4B). This power output is 13 times higher than that obtained using a drinking bird engine and an electromagnetic generator in previous experiments.[22]

The high output of our DB-THG enables us to effectively power small electronics using the natural energy from water evaporation in any ambient environment. We have demonstrated that 20 liquid crystal displays (LCDs) sized at 26 × 31 mm can directly be powered by the DB-THG (Figures 4D and S38; Video S4). Furthermore, the electricity generated by the DB-THG can be efficiently stored in commercial capacitors, charging them to above 10 V within several minutes (Figure 4C). In addition, a relatively larger capacitor of 1,000 μF is also charged to 1.5 V in 100 min (Figure S39). By utilizing a simple circuit with a capacitor, we can power various small commercial electronic devices like humidity sensors and calculators using the water evaporation energy harnessed by our DB-THG (Figure S40; Videos S5 and S6).

DISCUSSION

In summary, we have proposed an efficient power generation strategy by leveraging the latent heat of water evaporation and the triboelectric effect. For this, we designed a hydrovoltaic power generator (DB-THG) that combines the drinking bird engine and a TENG featuring low friction loss. The drinking bird engine sustainably collects the water evaporation energy and converts it into low-frequency mechanical motions. The TENG with patterned PP cotton as tribo-materials subsequently converts mechanical energy into electricity with minimum internal friction loss. Over 100 V voltage and around 40 μW power can be generated in ambient conditions by using natural water evaporation as a fuel, which enables directly powering 20 LCDs. Also, small electronic devices, such as humidity sensors and calculators, can also be powered by the DB-THG via a simple circuit containing a capacitor. Our DB-THG can be used as a highly efficient evaporation energy harvesting approach that has potential applications for both indoor and outdoor water-fueled electronics.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Zuankai Wang (zk.wang@polyu.edu.hk).

Materials availability

This study did not generate new unique materials.

Data and code availability

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

Fabrication of DB-THG

The main body of the drinking bird was taken from a commercial drinking bird toy (purchased from Alibaba; the photo and purchasing link of this toy can be found in Figure S3 and its legend, while the specification of the drinking bird is shown in Figure S5). The total length of the drinking bird is 15 cm. The outer diameters of the bird's head and the body are 25 and 32 cm, respectively. The outer diameter of the tube is 0.8 cm. The main ingredient of the liquid inside the drinking bird is CH_2Cl_2. The total weight of the main body of the drinking bird is about 24 g. The rod, frame of the rotor, stator, stand, and water container of the DB-THG were fabricated via 3D printing technology. The diameter of the sphere stator is 10.8 cm, and the angle of the fan-shaped rotor is 50°. The fan-shaped electrodes made of Cu tapes are manually fabricated on the stators. The PP cotton placed on the stator and the FEP films with the thickness of 30 μm were used as tribo-materials. The FEP films used in this study, which have a contact angle of approximately 109°, were not subjected to any surface treatment (Figure S42). The scanning electron microscope observation of these films is presented in Figure S43. The water container can be designed as various shapes. A semi-opened system with a small water tank connected with a closed container was used in this work for enhancing the water utilization (details of the specification of the DB-THG are shown in Figures S4–S12).

Characterization

The voltage, charge, and current output of the DB-THD were measured by using a programmable electrometer (Keithley 6514). The power output was calculated from the measured current data with $P = I^2R$, where P is power output, I is the measured current, and R is the load resistance. The generated electric energy is calculated by $E = \int I^2Rdt$, where t represents time. The measurements with varying temperature and humidity were conducted in a commercial temperature-controlled humidity chamber (ST-150LB, YISHITE INSTRUMENTS). Temperature and humidity meters were placed near the DB-THD for in the humidity chamber to accurately measure ambient conditions around the device (Figure S41).

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.device.2024.100318.

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AUTHOR CONTRIBUTIONS

Experiment design, Z.W. and H.W.; experiment performance and analysis, H.W., H.Z., X.Q., Y.J., Y.L., S.Y., Z.Y., S.G., S.W., and Z.W.; writing, Z.W., H.W., and S.W.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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REFERENCES

1. Zhang, Z., Li, X., Yin, J., Xu, Y., Fei, W., Xue, M., Wang, Q., Zhou, J., and Guo, W. (2018). Emerging hydrovoltaic technology. Nat. Nanotechnol. *13*, 1109–1119.
2. Stephens, G.L., Li, J., Wild, M., Clayson, C.A., Loeb, N., Kato, S., L'Ecuyer, T., Stackhouse, P.W., Lebsock, M., and Andrews, T. (2012). An update on Earth's energy balance in light of the latest global observations. Nat. Geosci. *5*, 691–696.
3. Cavusoglu, A.H., Chen, X., Gentine, P., and Sahin, O. (2017). Potential for natural evaporation as a reliable renewable energy resource. Nat. Commun. *8*, 617.
4. Chen, X., Goodnight, D., Gao, Z., Cavusoglu, A.H., Sabharwal, N., DeLay, M., Driks, A., and Sahin, O. (2015). Scaling up nanoscale water-driven energy conversion into evaporation-driven engines and generators. Nat. Commun. *6*, 7346.

5. Chen, X., Mahadevan, L., Driks, A., and Sahin, O. (2014). spores as building blocks for stimuli-responsive materials and nanogenerators. Nat. Nanotechnol. *9*, 137–141.
6. Ding, T., Liu, K., Li, J., Xue, G., Chen, Q., Huang, L., Hu, B., and Zhou, J. (2017). All-Printed Porous Carbon Film for Electricity Generation from Evaporation-Driven Water Flow. Adv. Funct. Mater. *27*, 1700551.
7. He, H., Zhao, T., Guan, H., Zhong, T., Zeng, H., Xing, L., Zhang, Y., and Xue, X. (2019). A water-evaporation-induced self-charging hybrid power unit for application in the Internet of Things. Sci. Bull. *64*, 1409–1417.
8. Li, J., Liu, K., Ding, T., Yang, P., Duan, J., and Zhou, J. (2019). Surface functional modification boosts the output of an evaporation-driven water flow nanogenerator. Nano Energy *58*, 797–802.
9. Sun, J., Li, P., Qu, J., Lu, X., Xie, Y., Gao, F., Li, Y., Gang, M., Feng, Q., Liang, H., et al. (2019). Electricity generation from a Ni-Al layered double hydroxide-based flexible generator driven by natural water evaporation. Nano Energy *57*, 269–278.
10. Xue, G., Xu, Y., Ding, T., Li, J., Yin, J., Fei, W., Cao, Y., Yu, J., Yuan, L., Gong, L., et al. (2017). Water-evaporation-induced electricity with nanostructured carbon materials. Nat. Nanotechnol. *12*, 317–321.
11. Zhang, N., Zhang, H., Xu, W., Gu, H., Ye, S., Zheng, H., Song, Y., Wang, Z., and Zhou, X. (2022). A droplet-based electricity generator with ultrahigh instantaneous output and short charging time. Droplet *1*, 56–64.
12. Jin, Y., Wu, C., Sun, P., Wang, M., Cui, M., Zhang, C., and Wang, Z. (2022). Electrification of water: From basics to applications. Droplet *1*, 92–109.
13. Li, L., Wang, X., Deng, W., Yin, J., Li, X., and Guo, W. (2023). Hydrovoltaic energy from water droplets: Device configurations, mechanisms, and applications. Droplet *2*, e77.
14. Xu, X., Yang, X., Zhang, Z., Hong, Y., Liu, S., Shan, Y., Peng, Z., Wang, S., Yao, X., and Yang, Z. (2023). Identification of metal–air batteries from water energy harvesters. Droplet *2*, e80.
15. Wang, H., Sun, Y., He, T., Huang, Y., Cheng, H., Li, C., Xie, D., Yang, P., Zhang, Y., and Qu, L. (2021). Bilayer of polyelectrolyte films for spontaneous power generation in air up to an integrated 1,000 V output. Nat. Nanotechnol. *16*, 811–819.
16. Huang, Y., Cheng, H., Yang, C., Zhang, P., Liao, Q., Yao, H., Shi, G., and Qu, L. (2018). Interface-mediated hygroelectric generator with an output voltage approaching 1.5 volts. Nat. Commun. *9*, 4166.
17. Zhang, Y., Guo, S., Yu, Z.G., Qu, H., Sun, W., Yang, J., Suresh, L., Zhang, X., Koh, J.J., and Tan, S.C. (2022). An Asymmetric Hygroscopic Structure for Moisture-Driven Hygro-Ionic Electricity Generation and Storage. Adv. Mater. *34*, e2201228.
18. Zhang, Y., Yu, Z., Qu, H., Guo, S., Yang, J., Zhang, S., Yang, L., Cheng, S., Wang, J., and Tan, S.C. (2022). Self-Sustained Programmable Hygroelectronic Interfaces for Humidity-Regulated Hierarchical Information Encryption and Display. Adv. Mater. e2208081.
19. Sun, Z., Wen, X., Guo, S., Zhou, M., Wang, L., Qin, X., and Tan, S.C. (2023). Weavable yarn-shaped moisture-induced electric generator. Nano Energy *116*, 108748.
20. Li, L., Feng, S., Bai, Y., Yang, X., Liu, M., Hao, M., Wang, S., Wu, Y., Sun, F., Liu, Z., and Zhang, T. (2022). Enhancing hydrovoltaic power generation through heat conduction effects. Nat. Commun. *13*, 1043.
21. Güémez, J., Valiente, R., Fiolhais, C., and Fiolhais, M. (2003). Experiments with the drinking bird. Am. J. Phys. *71*, 1257–1263.
22. Lorenz, R. (2006). Finite-time thermodynamics of an instrumented drinking bird toy. Am. J. Phys. *74*, 677–682.
23. Ng, L.M., and Ng, Y.S. (1993). The thermodynamics of the drinking bird toy. Phys. Educ. *28*, 320–324.
24. Vemulapalli, G.K. (1990). A Discourse on the Drinking Bird. J. Chem. Educ. *67*, 457–458.
25. Frank, D.L. (1973). The drinking bird and the scientific method. J. Chem. Educ. *50*, 211.
26. Uechi, H., and Uechi, S.T. (2020). Thermoelectric energy conversion of a drinking bird by disk-magnet electromagnetic induction. World J. Eng. Technol. *08*, 204–216.
27. Forstner, C., and Walker, M. (2020). Biographies in the History of Physics (Springer).
28. Yakov, P. (1936). Physics for Entertainment. Book 2.
29. Hillery, A.M. (1945). Activated Amusement Device (US Patent), pp. US2384168A.
30. Xu, W., Zheng, H., Liu, Y., Zhou, X., Zhang, C., Song, Y., Deng, X., Leung, M., Yang, Z., Xu, R.X., et al. (2020). A droplet-based electricity generator with high instantaneous power density. Nature *578*, 392–396.
31. Zi, Y., Guo, H., Wen, Z., Yeh, M.H., Hu, C., and Wang, Z.L. (2016). Harvesting Low-Frequency (<5 Hz) Irregular Mechanical Energy: A Possible Killer Application of Triboelectric Nanogenerator. ACS Nano *10*, 4797–4805.
32. Wu, C., Wang, A.C., Ding, W., Guo, H., and Wang, Z.L. (2019). Triboelectric Nanogenerator: A Foundation of the Energy for the New Era. Adv. Energy Mater. *9*, 1802906.
33. Wu, H., Wang, S., Wang, Z., and Zi, Y. (2021). Achieving ultrahigh instantaneous power density of 10 MW/m by leveraging the opposite-charge-enhanced transistor-like triboelectric nanogenerator (OCT-TENG). Nat. Commun. *12*, 5470.
34. Jiang, T., Chen, X., Yang, K., Han, C., Tang, W., and Wang, Z.L. (2016). Theoretical study on rotary-sliding disk triboelectric nanogenerators in contact and non-contact modes. Nano Res. *9*, 1057–1070.
35. Nguyen, V., and Yang, R. (2013). Effect of humidity and pressure on the triboelectric nanogenerator. Nano Energy *2*, 604–608.
36. Shen, J., Li, Z., Yu, J., and Ding, B. (2017). Humidity-resisting triboelectric nanogenerator for high performance biomechanical energy harvesting. Nano Energy *40*, 282–288.
37. Xu, C., Wang, A.C., Zou, H., Zhang, B., Zhang, C., Zi, Y., Pan, L., Wang, P., Feng, P., Lin, Z., and Wang, Z.L. (2018). Raising the Working Temperature of a Triboelectric Nanogenerator by Quenching Down Electron Thermionic Emission in Contact-Electrification. Adv. Mater. *30*, e1803968.
38. Wang, A.C., Zhang, B., Xu, C., Zou, H., Lin, Z., and Wang, Z.L. (2020). Unraveling Temperature-Dependent Contact Electrification between Sliding-Mode Triboelectric Pairs. Adv. Funct. Mater. *30*, 1909384.
39. Harris, I.A., Lim, M.X., and Jaeger, H.M. (2019). Temperature dependence of nylon and PTFE triboelectrification. Phys. Rev. Mater. *3*, 085603.
40. Liu, X., Gao, H., Ward, J.E., Liu, X., Yin, B., Fu, T., Chen, J., Lovley, D.R., and Yao, J. (2020). Power generation from ambient humidity using protein nanowires. Nature *578*, 550–554.