**INTRODUCTION**

As a ubiquitous substance on the planet, bubbles are widely exploited in the biological world (1, 2) and various industrial applications (3, 4). In nature, tiny cavitation bubbles can be used as a weapon by a snapper shrimp to stun or even kill prey animals (5, 6), whereas large bubbles produced by humpback whales form into a network ed in the biological world (7). As a ubiquitous substance on the planet, bubbles are widely exploited in various industrial applications. For instance, bubbles have been extensively explored as energy carriers ranging from boiling heat transfer and targeted cancer diagnosis (8). Yet, despite notable progress, the kinetic energy inherent in small bubbles remains difficult to harvest. Here, we develop a transistor-inspired bubble energy generator for directly and efficiently harvesting energy from small bubbles. The key points lie in designing dielectric surface with high-density electric charges and tailored surface wettability as well as transistor-inspired electrode configuration. The synergy between these features facilitates fast bubble spreading and subsequent departure, transforms the initial liquid/solid interface into gas/solid interface under the gating of bubble, and yields an output at least one order of magnitude higher than existing studies. We also show that the output can be further enhanced through rapid bubble collapse at the air/liquid interface and multiple bubbles synchronization. We envision that our design will pave the way for small bubble-based energy harvesting in liquid media.

**ENGINEERING**

**Bubble energy generator**

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Bubbles have been extensively explored as energy carriers ranging from boiling heat transfer and targeted cancer diagnosis. Yet, despite notable progress, the kinetic energy inherent in small bubbles remains difficult to harvest. Here, we develop a transistor-inspired bubble energy generator for directly and efficiently harvesting energy from small bubbles. The key points lie in designing dielectric surface with high-density electric charges and tailored surface wettability as well as transistor-inspired electrode configuration. The synergy between these features facilitates fast bubble spreading and subsequent departure, transforms the initial liquid/solid interface into gas/solid interface under the gating of bubble, and yields an output at least one order of magnitude higher than existing studies. We also show that the output can be further enhanced through rapid bubble collapse at the air/liquid interface and multiple bubbles synchronization. We envision that our design will pave the way for small bubble-based energy harvesting in liquid media.

In this work, we develop a previously unidentified bubble energy generator that directly and efficiently harvests energy from small bubbles without using moving components. The key innovation lies in...
tailoring the surface wettability of dielectric material for preferential bubble mobility and transport that suppresses the unwanted screening effect as well as designing transistor-inspired electrode configuration for efficient charge transfer even in a water environment. We also show that the transistor-inspired bubble energy generator (TBENG) design concept is generic to small bubble energy harvesting even in the air, in which the fast bubble collapse remarkably accelerates the charge transfer and leads to boosted output performance.

RESULTS

The TBENG features a two-electrode design, with an indium tin oxide (ITO) electrode sandwiched between a glass substrate and an electret material [polytetrafluoroethylene (PTFE)] and the other platinum (Pt) electrode positioned in water (Fig. 1, A and B). In our design, the electret PTFE is treated with high surface charge density to serve as the charge reservoir, while imparting ingenious surface wettability to promote preferential bubble motion. The configuration of our design is analogous to a field effect transistor that consists of source, gate, and drain terminals. The electret layer in conjunction with the underlying ITO electrode can be treated as the source terminal, the second electrode (Pt) placed in water behaves like a drain terminal for charge releasing, and the moving bubble that mediates the charge release from the PTFE surface serves as a gate. With such a configuration, we expect that when a bubble impinges on the surface of TBENG, the original liquid/solid interface can be translated into a gas/solid interface, which will drive charge transfer between two electrodes for the boosted output.

The electret layer PTFE and the underlying ITO electrode of TBENG were prepared using drop-casting and patterning processes, respectively. We first patterned the ITO electrode on a flat glass, followed by uniformly depositing a thin layer of the liquid PTFE precursor on the entire surface and thermal curing (fig. S1). As evidenced by scanning electron microscopy, atomic force microscopy (fig. S2), and optical measurements (fig. S3), the PTFE layer is smooth and transparent. The PTFE layer and ITO electrode can also be fabricated on flexible substrates with various morphologies (fig. S4). The PTFE surface immersed in the underwater environment exhibits an apparent bubble contact angle (BCA; \( \theta_0 \)) of \(-45^\circ\), and its wettability can be modified by plasma treatment (fig. S5).

Figure 1 (C and D) shows the representative output of TBENG in response to an impinging bubble of 100 \( \mu \)l released from a nozzle 18.0 mm below the device. For the TBENG with a BCA of 65\(^\circ\), the open-circuit output voltage and the short-circuit current are measured to be \( \sim 40.3 \) V and 2.4 \( \mu \)A, respectively, which are approximately 56.5 and 34.3 times higher than that of the control device without the utility of the two-electrode design. The amount of transferred charges \( Q \) from the Pt electrode to ITO is measured to be \( \sim 20.0 \) nC, which is 40.4 times higher than that of the control device (Fig. 1E). The instantaneous peak power density is 56.4 W m\(^{-3}\) under a load resistance \( R_L \) of 100 megohms (fig. S6), which is two orders of magnitude higher than that of the control device without the utility of two-electrode design. Such a boost in electric output could also be reflected by lighting up 35 light emission diodes with a tiny bubble of 100 \( \mu \)l (Fig. 1F). Notably, the TBENGs with varying electrode parameters including materials, sizes, and spatial distributions also sustain electricity output without notable attenuation (fig. S7), suggesting that electricity generation is not sensitive to the specific electrode parameters and thus rendering excellent adaptability for energy harvesting in dynamic, complex environments.
The physical rationale of the TBENG can be explained in fig. S8A. Specifically, placing the Pt electrode in water connects the PTFE, water, and ITO electrode into a closed circuit. Before the contact of the bubble with the PTFE surface, the surface charges that are pre-stored on the PTFE are screened by the counterions in water, and there is no charge transfer between two electrodes. When an impacting bubble contacts the PTFE surface, the initial water/PTFE interface is transformed into the air/PTFE interface, and the surface charges of PTFE that are newly exposed to air bubble would electrostatically induce charges on the ITO electrode, leading to the charge transfer between the two electrodes. In contrast, in the case of the control device with a single electrode, most of the surface charges on PTFE are screened by the charges on the ITO electrode (fig. S8B). Moreover, there is no formation of a closed circuit between water, the PTFE surface, and ITO, as opposed to the case of the two-electrode design, resulting in limited charge transfer despite the contact of bubble with the PTFE surface.

Figure 2A plots the time-dependent variation of measured output voltage $V$ obtained from TBENG. Upon impacting on the PTFE surface at 0 ms, the small bubble spreads, recoils, and lastly departs with a contact time $\tau$ of 40.0 ms, exhibiting a time-dependent gas/surface contact area. Careful inspection indicates that the maximum output voltage occurs at 9.0 ms, during which the bubble is still in the stage of spreading. At 20.0 ms, the bubble reaches a maximum diameter $d_{\text{max}} \sim 8.3$ mm, and its output voltage drops to 0 V. The subsequent bubble recoiling leads to a negative output voltage, and when the bubble completely departs from the surface, the output returns to zero. Figure 2A also shows the existence of a high synchronization between the output voltage and the change rate in the bubble/surface contact area in the entire spreading and recoiling process (movie S1), strongly suggesting that the energy generation is gated by the moving bubble.

In an underwater environment, the PTFE surface of TBENG is inevitably covered by a water film that is expected to block the charge generation and transfer on PTFE, which is in contrast to droplet-based...
electricity generation functioning in an air environment (30, 31). To reveal the elimination of such an unwanted screening effect in our design, we further visualized microscopic behaviors of the water film on the PTFE surface. As shown in Fig. 2B (movie S2), for TENG with a BCA of 65°, the water film can be completely drained by an impacting bubble, transforming the initial liquid/solid interface into a gas/solid interface and thereby eliminating the unwanted screening effect caused by the water film. In contrast, for TENG with a BCA of 135°, the coverage of a continuous water film between the impacting bubble and the solid substrate screens the charge release from PTFE, suppressing the electrostatic charge generation on ITO and subsequent output (Fig. 2C and fig. S9). Figure 2D shows the output voltages measured from devices with varying wettability, suggesting that the energy generation is closely regulated by the surface wettability.

To reveal the role of surface wettability on the energy generation, we further measured the transferred charge density \( \sigma \) and analyzed the bubble mobility on TENG with varying BCAs. As shown in Fig. 2E, as the BCA of PTFE increases from ~45° to ~115°, the \( \sigma \) value first increases and then drops owing to the coverage of the water film at higher BCAs, a trend inconsistent with our measurement in Fig. 2D. In contrast, as the BCA increases from ~45° to ~115°, the interfacial energy for overcoming the van der Waals attraction between gas molecules and PTFE, defined as the interaction energy to quantify the bubble mobility on TENG with varying BCAs, decreases linearly from 149.42 to 62.89 kJ/mol based on molecular dynamics (MD) simulations (Fig. 2E). Combining these two results suggests that there might exist a crossover in the optimal wettability for the maximum output. More quantitatively, assuming that the contact area between bubble and TENG is circular, simple circuit and hydrodynamic (32) analysis shows the voltage output \( V \sim \frac{dQ}{dt} \sim \sigma(\theta_d^3 - \theta_0^3)\gamma/\mu \), where \( \theta_d \) is the dynamic contact angle, \( \gamma \) and \( \mu \) are the surface tension and viscosity of water, respectively (see Materials and Methods). As illustrated in Fig. 2F, under varying BCAs, the instantaneous peak value of measured voltage \( V_p \) via \( \sigma(\theta_d^3 - \theta_0^3)\gamma/\mu \) collapses into a linear curve, confirming the essential role of surface wettability on energy generation.

We next considered the scenarios of multiple small bubbles to simulate practical application. Different from a single small bubble, multiple small bubbles display both synchronization and nonsynchronization modes depending on the spatial and temporal conditions for bubble release (movie S3). Figure 3 (A–I) shows a representative synchronization mode, where two bubbles are concurrently released with a spatial distance larger than \( d_{\text{max}} \). In the nonsynchronization mode, bubbles are released at an interval less than the contact time \( \tau \) of individual bubbles, and as a result, their spreading and recoiling processes are coupled together (Fig. 3, A–II). Accordingly, synchronous bubbles exhibit an enlarged change rate in bubble/surface contact area (Fig. 3B) and output voltage (Fig. 3C) as opposed to that in the nonsynchronization mode. Note that the nonsynchronization mode can also be suppressed by enlarging the time interval or spatial spacing for bubble release.

The efficient electricity generation in an underwater environment can be extended to an air environment for enhanced output. At the air/water interface, small bubbles in contact with a solid substrate are easily collapsed. Figure 3D shows the snapshots of a bubble in contact with a PTFE above in the air, which collapses within 5.2 ms, representing 75% reduction in the bubble departure time (movie S4). Moreover, the air environment also eliminates the unwanted screening effect caused by the water film. These two advantages leads to 142.9%
enhancement in the measured output voltage (~70 V) as compared to that of TBENG in an underwater environment (Fig. 3E). The average energy density is measured to be ~2.14 ml/liter, which surpasses existing small bubble-based energy generators (Fig. 3F) (20, 25, 33–36).

DISCUSSION
The TBENG is especially suitable for off-grid regions characterized by varied salt concentrations (Fig. S10) such as underwater and marine environments where power supplies are not achievable. In these environments, maintaining long-term operation of electronic devices such as health monitoring devices is challenging. Current off-grid power supplies, such as using long-distance electricity transportation by electric wires or replenishing energy by disposable batteries, are cost-ineffective, resources-dependent, and eco-unfriendly. The electricity generated from bubbles can be stored in capacitors (Fig. 4A), serving as a sustainable, clean, and real-time source for powering health monitoring devices. TBENG can also be integrated with a multifunctional sensor to simultaneously monitor the temperature, humidity, and time without the need of energy replenishment, as evidenced in Fig. 4B and movie S5. We also designed a wireless temperature sensor with intermittent data transmitting mode (Fig. 4C), which can be easily powered by charging a 15-μF capacitor to 4 V by TBENG (Fig. 4D), demonstrating the great potential for long-term health monitoring application in an off-grid environment (movie S5).

Fundamentally, gated by small bubbles, the TBENG directly harnesses high-density electric charges stored on the PTFE to boost electrical output performance. However, in droplet electricity generation, the stored charges can be released within microseconds to yield a high instantaneous power density. In contrast, the charge release in TBENG involves transforming the original liquid/solid interface into a gas/solid interface, a process at a time scale three magnitudes smaller than that of a droplet-based electricity generator. Nonetheless, owing to the special water environment associated with a large viscosity, the TBENG has a longer electricity generation duration (40.0 ms) and a higher surface charge density (0.378 mC/m²) resulting from the reduced spreading area, thereby exhibiting an average power only 10 times lower than that of the droplet-based electricity generator (30). Despite the relatively lower average power of the TBENG, the energy conversion efficiency of our TBENG, defined as the harvested electrical energy relative to the input energy of an impinging bubble, is calculated to be roughly 1.0%, which is comparable to that of a droplet-based electricity generator (30). We envision that the innovation of TBENG will point many applications in underwater and offshore operations otherwise impossible to directly harvest energy from small bubbles.

MATERIALS AND METHODS
Materials
Deionized water, ethanol (Sigma-Aldrich; 97%), nitric acid (Sigma-Aldrich; 70%), hydrochloric acid (Sigma-Aldrich; 37%), and a PTFE precursor (Dupont AF 601S2; 6 weight%) were directly used without further purification. The PTFE precursor consists of PTFE dissolved in 4,5-difluoro-2,2-bis (trifluoromethyl)-1,3-dioxole (a low-boiling organic solvent) without any extra additives. The size of the commercial ITO glass is 60 mm by 30 mm by 1.1 mm. The thickness of ITO thin film on the glass substrate is 10 μm.

Fabrication of TBENG
We fabricated the TBENG device by the following steps. First, a piece of ITO glass was ultrasonically cleaned in an ethanol bath for 15 min. Second, this ITO glass was etched to obtain a predesigned ITO pattern on the glass substrate using an acid solution that is composed of 50 ml of hydrochloric acid, 3 ml of nitric acid, and 50 ml of deionized water. The whole etching time was 20 min. Third, 300 μl of the PTFE precursor was uniformly deposited on the patterned ITO glass through drop-casting. Then, the sample was moved to an oven and cured at 120°C for 20 min. As the solvent in the PTFE precursor completely evaporated, the liquid PTFE precursor was transformed into a smooth and dense PTFE film. Thereafter, we adjusted the surface wettability of the sample through plasma treatment. Last, we connected the as-prepared sample with one end of an electric wire and inserted the other end of the electric wire in water.

Characterization and electrical measurement
We used an air pump to produce gas bubbles with a frequency of 5 Hz in tap water with an ion concentration of 3.1 mM. The volume of bubbles is fixed at 100.0 μl by controlling the gas flow in the air pump (10.0 ml/min), the diameter of the dispenser (4.0 mm), the distance between the PTFE surface and the dispenser outlet (100.0 mm), and the water depth (18.0 mm). If not specified, all experiments were conducted in tap water and the sample was fixed at a tilting angle of 45°. We recorded the contact and detachment dynamics of gas bubbles using a high-speed camera (Photon FASTCAM SA4) at a typical recording speed of 3000 frames per second. The output voltage of TBENG was measured using an oscilloscope (Rohde and Schwarz, RTE1024) equipped with a high-impedance (100 megohms) probe. We measured the current and the charges transferred between the ITO and the Pt electrode using the oscilloscope coupled with a low-noise current preamplifier (Stanford Research System Model SR570) and a nanocoulomb meter (Monroe model 284), respectively.

Calculation of power, energy, and energy conversion efficiency
The instantaneous peak power $P$ generated from a bubble impinging on TBENG is calculated by $P = V_p^2 / R_L$, where $R_L$ is load resistance, and $V_p$ is the instantaneous peak value of measured voltage. According to the measured voltage of 23.7 V at $R_L = 100.0$ megohms, the maximum power density is calculated at 5.64 μW, which corresponds to a power density of 56.4 W/m³ with a bubble volume $V_b = 100.0$ μl. The energy density generated from a bubble is calculated by $E = \int_0^T V(t) \, dt / R_L$, where $V(t)$ is the measured time-evolved voltage generated from a bubble. According to the measured $V(t)$ in Fig. 2A, we calculated the energy generated from a bubble to be 172.0 nJ and a corresponding energy density of 1.72 J/m³.

The energy conversion efficiency $\eta$ of our TBENG, defined as the harvested electrical energy $E$ relative to the input energy $E_{in}$ (buoyancy work) of an impinging bubble, is expressed as

$$\eta = \frac{E}{E_{in}} = \frac{E}{\rho V_b g s}$$

where $\rho$, $g$, $V_b$, and $s$ are the water density (1000.0 kg/m³), gravitational acceleration (9.8 m/s²), bubble volume (100.0 μl), and water depth (18.0 mm), respectively. By calculation, the energy conversion efficiency of TBENG from a bubble is ~1.0%.
Circuit and hydrodynamic analysis
The generated voltage $V$ of TBENG is proportional to the current $I$ across the load resistance, $R_L$, which can be expressed as $V = I R_L$, where $Q$ is the amount of electric charges transferred in the electric circuit. Substituting $dQ/dt = \sigma (dA_{CCS}/dt)$ gives $V = R_L \sigma (dA_{CCS}/dt)$, where $\sigma$ is the measured charge density on TBENG surface. Assuming that the contact area between gas bubble and the TBENG surface is circular, we have $V = R_L \sigma (dA_{CCS}/dt) \sim R_L \sigma (dr/dt)$, where $r$ is the base radius of bubble on the PTFE. According to a hydrodynamic model that describes the spreading bubble, $V$ can be expressed as

$$V \sim R_L \sigma (\theta_d^3 - \theta_0^3) / [9 \mu \ln(r/l)]$$

where $\gamma$ is the surface tension of water, $\mu$ is the viscosity of water, $\theta_d$ is the dynamic contact angle, $l$ is the slip length, and the order of $\ln(r/l)$ is about 14. Thus, $V$ can be scaled as $V \sim \sigma (\theta_d^3 - \theta_0^3) \gamma / \mu$.

MD Simulation
To present the microscopic characteristics of the bubbles on the PTFEs with different surface wettability, we carried out MD simulations with the GROMACS 2019.2 package. The simulation system has a box size of 33.30 nm by 3.33 nm by 16.22 nm and is made up of 47,139 H2O molecules, 1355 N2 molecules, and a PTFE substrate, in which the PTFE is represented by a rigid atomic layer. Water molecules were described by the simple point charge/extended (SPC/E) model because of its good performance in reproducing several properties of liquid water such as surface tension and density. The force field parameters for N2 were taken from the previous studies. The Lennard-Jones potentials between unlike atoms of water and nitrogen were constructed by the Lorentz-Berthelot combination rule, in which an arithmetic average is used to calculate $\sigma$ (Lennard-Jones collision diameter) while a geometric average is adopted for calculating $\epsilon$ (potential well depth). To mimic different wettability of PTFE substrate, we adjusted the Lennard-Jones potentials between substrate and water accordingly.

Each initial configuration of the simulation system was first optimized with the energy minimization algorithm of steepest descent, after which the MD simulation was conducted under the NVT ensemble with the periodic boundary condition applied in all directions. To correspond to the temperature in the experiments, the temperature in the MD simulation was maintained at 299.15 K by the $V$-rescale thermostat algorithm. The nonbonded Lennard-Jones interactions were truncated at 1.1 nm. The Smooth Particle-mesh Ewald method was used to accurately treat the long-range electrostatic interactions with a real-space cutoff of 1.1 nm. The H–O bond in the water molecule was under constraint with the algorithm of Linear Constraint Solver. For each system, the simulation was performed for 4 ns with a time step of 1 fs, and the last 2-ns trajectory at equilibrium state was used for the subsequent analyses. All modeling and simulation outcomes are visualized by Visual Molecular Dynamics.

SUPPLEMENTARY MATERIALS
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REFERENCES AND NOTES
1. R. S. Seymour, S. K. Hetz, The diving bell and the spider: The physical gill of Argyro Beta aquatica. J. Exp. Biol. 214, 2175–2181 (2011).
2. W. Bartholli, T. Schimmelt, S. Wiersch, K. Koch, M. Brede, M. Barczewski, S. Walheim, A. Weis, A. Kellenmaier, A. Leder, The Salvinia paradox: Superhydrophobic surfaces with hydrophilic pins for air retention under water. Adv. Mater. 22, 2325–2328 (2010).
3. S. R. Gonzalez-Avila, M. N. Dang, S. Arunachalam, E. M. Domingues, C. D. Ohl, Mitigating cavitation erosion using biomimetic gas-entrapping microtextured surfaces (GEMS). Sci. Adv. 6, eaad192 (2020).
4. T. J. Jones, E. Jambon Pulillet, J. Marthelot, P. T. Brun, Bubble casting soft robotics. Nature 599, 229–233 (2021).
5. D. Lohse, B. Schmitz, M. Versluys, Snapping shrimp make flashing bubbles. Nature 413, 477–478 (2001).
6. M. Versluys, How snapping shrimp snap: Through cavitating bubbles. Science 289, 2114–2117 (2000).
7. S. L. Ceccio, Friction drag reduction of external flows with bubble and gas injection. Annu. Rev. Fluid Mech. 42, 183–203 (2010).
8. A. Steinberger, C. Cotton-Bizzone, P. Kleinn, E. Charlaix, High friction on a bubble mattress. Nat. Mater. 6, 665–668 (2007).
9. H. Forster, N. Zuber, Dynamics of vapor bubbles and boiling in gas, N. Nanotechnol. 16, 1403–1412 (2021).
10. K. Krupenkin, A. Taylor, Reverse electroosmotic as a new approach to high-power energy harvesting. Nat. Commun. 2, 448 (2011).
11. F. R. Fan, Z. Q. Tian, Z. L. Wang, Flexible triboelectric generator. Nano Energy 1, 328–334 (2012).
12. W. Xu, X. Zhou, C. Hao, H. Zheng, Y. Liu, X. Yan, Z. Yang, M. Leung, X. C. Zeng, R. X. Xu, Z. Wang, SLIPS-TENG: Robust triboelectric nanogenerator with optical and charge transparency using a slippery interface. Natl. Sci. Rev. 6, 540–550 (2019).
13. J. Yin, X. Li, J. Yu, Z. Zhang, J. Zou, Generating electricity by moving a droplet of ionic liquid along graphene. Nat. Nanotechnol. 9, 378–383 (2014).
14. F. Zhao, Y. Liang, H. Cheng, L. Jiang, L. Qi, Highly efficient moisture-enabled electricity generation from graphene oxide frameworks. Energ. Environ. Sci. 9, 912–916 (2016).
15. B. Fan, A. Bhattacharya, P. Bandaru, Enhanced voltage generation through electrolyte flow on liquid-filled surfaces. Nat. Commun. 9, 1–7 (2018).
16. X. Liu, H. Gao, J. E. Ward, X. Liu, B. Yin, T. Fu, J. Chen, D. R. Lovley, J. Yao, Power generation from ambient humidity using protein nanowires. Nature 550, 550–554 (2020).
17. T. H. Hsu, S. Manakasettharn, J. A. Taylor, K. Krupenkin, Bubbler: A novel ultra-high power density energy harvesting method based on reverse electroosmotic. Sci. Rep. 5, 16537 (2015).
18. Z. Guan, P. Li, Y. Wen, Y. Du, T. Han, X. Jie, Efficient underwater energy harvesting from bubble-driven pipe flow. Appl. Energy 295, 116987 (2021).
19. Y. Du, Z. Guan, D. Chen, J. Ye, P. Li, Y. Wen, Broadband rotary hybrid generator for wide-flow-rate fluid energy harvesting and bubble power generation. Energ. Convers. Manage. 250, 114833 (2021).
20. N. Clement, K. Nishiguchi, J. F. Dufreche, D. Guerin, A. Fujimura, D. Vaillama, Water electrolysis and energy harvesting with zero-dimensional ion-sensitive field-effect transistors. Nano Lett. 13, 3903–3908 (2013).
21. C. Fan, C. Wu, G. Wen, Development of gas–liquid two-phase flow pattern sensor of coalbed methane based on the principle of triboelectric nanogenerator. Nano Letters 20, 5050 (2020).
22. Y. Song, W. Zhao, Y. Huang, D. Li, Underwater bubble detection and counting by a dynamic changing solid-liquid interfacial process. Sens. Actuators B Chem. 329, 129083 (2021).
23. C. Li, X. Liu, D. Yang, Z. Liu, Triboelectric nanogenerator based on moving bubble in liquid for mechanical energy harvesting and water level monitoring. Nano Energy 95, 106998 (2022).
24. X. Cheng, L. Miao, H. Chen, Y. Song, Z. Su, X. Chen, H. Wang, M. Zhang, H. Zhang, paper presented at the 30th International Conference on Micro Electro Mechanical Systems (MEMS), Las Vegas, NV, 22 January 2017.
25. X. Zhang, G. Zhang, L. Zhang, P. Li, M. Cheng, J. Zhao, Y. Zhang, H. Su, T. Tan, F. Shi, Functionally cooperating mini-generator: From bacterial fermentation to electricity. Adv. Funct. Mater. 29, 1900879 (2019).
26. D. Jiang, J. Leon, S. K. Chung, Acoustic bubble-powered miniature rotor for wireless energy harvesting in a liquid medium. Sens. Actuators A Phys. 276, 296–303 (2018).
27. W. Li, W. Zhang, L. Zhou, Q. Shen, W. Shang, Vapor bubble induced electric current generation. Pure Appl. Chem. 93, 1247–1254 (2021).
28. E. J. Beck, Ocean thermal gradient power plant, U.S. Patent no: US 3,967,449 A (1976).
29. W. Xu, H. Zheng, Y. Liu, X. Zhou, C. Zhang, Y. Song, X. Deng, M. Leung, Z. Yang, R. X. Xu, Z. L. Wang, X. C. Zeng, Z. Wang, A droplet-based electricity generator with high instantaneous power density. Nature 578, 392–396 (2020).
30. H. Wu, N. Mendel, D. van den Ende, G. Zhou, F. Mugele, Energy harvesting from drops impacting onto charged surfaces. Phys. Rev. Lett. 125, 073801 (2020).
31. C. M. Phan, A. V. Nguyen, G. M. Evans, Assessment of hydrodynamic and molecular-kinetic models applied to the motion of the dewetting contact line between a small bubble and a solid surface. Langmuir 19, 6796–6801 (2003).
33. J. Chen, H. Guo, J. Zheng, Y. Huang, G. Liu, C. Hu, Z. L. Wang, Self-powered triboelectric micro liquid/gas flow sensor for microfluidics. ACS Nano 10, 8104–8112 (2016).
34. K. R. Wijewardhana, T. K. Ekanayaka, E. N. Jayaweera, A. Shahzad, J. K. Song, Integration of multiple bubble motion active transducers for improving energy-harvesting efficiency. Energy 160, 648–653 (2018).
35. K. R. Wijewardhana, T. Z. Shen, J. K. Song, Energy harvesting using air bubbles on hydrophobic surfaces containing embedded charges. Appl. Energy 206, 432–438 (2017).
36. Y. Yang, J. Park, S. H. Kwon, Y. S. Kim, Fluidic active transducer for electricity generation. Sci. Rep. 5, 15695 (2015).

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