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RESEARCH ARTICLE

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A droplet-based electricity generator incorporating Kelvin water dropper with ultrahigh instantaneous power density

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Abstract

Harvesting renewable water energy in various formats such as raindrops, waves, and evaporation is one of the key strategies for achieving global carbon neutrality. The recent decade has witnessed rapid advancement of the droplet-based electricity generator (DEG) with a continuous leap in the instantaneous output power density from 50 W/m^2 to several kW/m^2. Despite this, further pushing the upper limit of the output performance of DEG is still constrained by low surface charge density and long precharging time. Here, we report a DEG incorporating the Kelvin water dropper (K-DEG) that can generate an ultrahigh instantaneous power density of 10^5 W/m^2 upon one droplet impinging. In this design, the Kelvin water dropper continuously replenishes the high density of surface charges on DEG, while DEG fully releases these surface charges into electric output. K-DEG with such a high output can directly light five 6-W commercial lamps and even charge a cellphone by using falling droplets.

INTRODUCTION

Global carbon neutrality demands the exploitation of green, low-carbon, and renewable energy sources to replace conventional carbon-intensive fossil fuel-based energy sources.[1] Water, as a widely accessible and renewable energy source, holds an immense amount of energy estimated at 60 petawatts (10^{15} W) per year, several orders of magnitude greater than the global electricity consumption.[2] Although significant progress has been made in harvesting high-frequency and centralized hydrodynamic energy using electromagnetic generators, efficiently harvesting low-frequency and decentralized water energy in various forms such as raindrops,[3] river/ocean waves,[4–6] tides,[7] and even moisture[8–10] remains a challenge. The past decade has witnessed rapid development in harvesting energy from these underutilized water energy such as piezoelectric energy harvesters,[11,12] hydrovoltaic technology,[13–18] reverse electrodialysis,[19–22] and triboelectric nanogenerator.[23–30] Showing a great leap in power density and efficiency by several orders of magnitude, a recently reported droplet-based electricity generator with transistor-inspired architecture overcomes the limitation of interfacial effect in conventional design, providing a new route to efficiently harvest water energy.[31] Triggered by this finding, a wave of progress has been accomplished to generate electricity at various interfaces such as

Yang Li and Xuezhi Qin contributed equally to this study.

liquid–liquid,[32,33] liquid–solid,[34–36] and liquid–gas interface,[37] from single droplet to droplet arrays,[38] from bubbles to water waves,[39] with a continuous leap in peak power density from 50 to 10^3 W/m^2.[40]

Despite the significant progress, the output performance of droplet-based electricity generator (DEG) is still constrained by the long precharging time and low surface charge density.[40] First, a DEG generates electricity from the surface charge, which can be generated from the continuous liquid–solid contact electrification during droplet impinging.[31] Thus, forming a preferential high-density surface charge on DEG requires a long charging time of up to 1 h of droplet impingement, which is challenging in applications requiring frequent power supplies.[31] Second, surface charges generated from the liquid–solid contact electrification are strongly dependent on the nature of the materials, in particular, the electrochemical potential difference between the DEG surface materials and water, leading to a low surface charge density not larger than 180 μC/m^2.[31] Even though the surface charge density of DEG can be increased by an additional precharging method such as the electrowetting assisted charge injection or contact electrification with other counterpart materials (aluminum foil as an example),[41,42] these methods are involved with additional energy input and the resulted charges are suspected to low stability owing to the inevitable counter-ions adsorption, especially in an aqueous environment during long-term operation.[32]

Here, we develop a droplet-based electricity generator incorporating a Kelvin water dropper (K-DEG) that can attain an ultrahigh surface charge density of 358 μC/m^2 within a short charging time of less than 1 s. Different from previous DEGs, the key of K-DEG lies in the rational integration of DEG with the Kelvin water dropper. The Kelvin water dropper can instantly inject abundant charges on the surface of the dielectric layer of DEG as a result of corona discharge, while DEG can fully release these surface charges into electricity generation upon droplet impinging. With such a high-density surface charge, K-DEG can generate an enormously boosted transferred charge of 201 nC, output voltage up to 2000 V, and instantaneous power density over 10^5 W/m^2 from one droplet impinging (100 μL). Remarkably, the Kelvin water dropper can constantly replenish a high-density surface charge on the DEG surface during the corona discharge, mitigating the degradation of surface charge facing in the previously reported precharging method. With such a robust and high output performance, K-DEG can directly drive 40 liquid crystal displays (LCDs) or five 6-W bulbs upon one droplet impingement and even charge a mobile phone with a power management circuit. We anticipate that K-DEG with high instantaneous output performance not only sets a record of high-power DEG but also provides an elegant route to superimpose DEG with other droplet energy harvesters in a linear manner for efficiently harvesting droplet energy.

RESULTS AND DISCUSSION

Figure 1a,b shows the typical configuration of the K-DEG, which features two interactive components: a Kelvin water dropper and a DEG. To generate the high-density surface charge on the DEG surface, we placed the discharging needle connecting to the Kelvin water dropper above the center of the DEG surface made of fluorinated ethylene propylene (FEP) at a distance of around 2 cm (Figure 1c). Owing to a couple of electrostatic induction and self-excited feedback loop, we hypothesize that the Kelvin water dropper accumulates sufficient electrostatic charges with continuous feed-in droplets (Supporting information: Note 1 and Movie S1), therefore generating a high voltage between the discharging needle and the DEG surface (Supporting information: Figure S1). This voltage can grow to trigger the onset of corona discharge (Supporting information: Figure S2), resulting in the electrostatic injection of a large number of ionized charges (with polarity same as that of the discharging needle) onto the FEP surface and thereby increasing the surface charge density. Note that the electrical polarity of the Kelvin water dropper is random depending on the polarity of the charges carried by falling droplets (Supporting information: Figure S3). In this work, we ensured that the FEP surface is negatively charged by introducing simple electrostatic interference (see the Materials and methods section and Supporting information: Figure S4). To achieve the preferred electrical output performance, we leverage the DEG with transistor-like architecture to fully release the injected surface charge on FEP into electricity generation. Maintaining both the merit of Kelvin water dropper and transistor-inspired DEG, the developed K-DEG can obtain a stable high-density surface charge, therefore achieving efficient droplet energy harvesting. K-DEG enables an enormously boosted open-circuit output voltage of 2000 V and a short-circuit current of 4 mA (Figure 1d,e), which are, respectively, around eight times and 16 times higher than that from the controlled DEG without the Kelvin water dropper. Moreover, the maximum instantaneous power density of our K-DEG is about 2.6 kW/m^2 upon tap water droplet impingement and over 10^5 W/m^2 upon droplet impingement of 200 mM NaCl solution (Supporting information: Figures S5 and S6), far beyond that of previous reports. Such a high output can be reflected by instantaneously driving a 6-W bulb with a K-DEG (Figure 1f).

To understand the boost output of the K-DEG, we analyze the charge transfer process by examining the time-dependent evolution of the output current and charge (Figure 2a). As shown in Figure 2b,c, the measured short-circuit current shows two significant peaks upon the droplet impinges on our device, which, respectively, correspond to the transferred charge Q_1 of 109 nC and Q_2 of 92 nC. Upon a droplet impacting on the surface of FEP and touching the top electrode, a discharge current first occurs between the droplet and Kelvin water dropper, leading to the transferred charge Q_1 that comes from the Kelvin water dropper into the external circuit through the droplet channel (Figure 2a,ii). Such a process can be demonstrated by the voltage variation of the Kelvin water droplet. As shown in Figure 2d, the voltage of the Kelvin water dropper first increases rapidly before droplet impingement and then shows a sudden drop and nearly turns to zero upon the droplet impinging, which, respectively, represents a self-charging process and a discharging process of the Kelvin water dropper toward the droplet. Subsequent to the discharging current of the Kelvin water dropper,

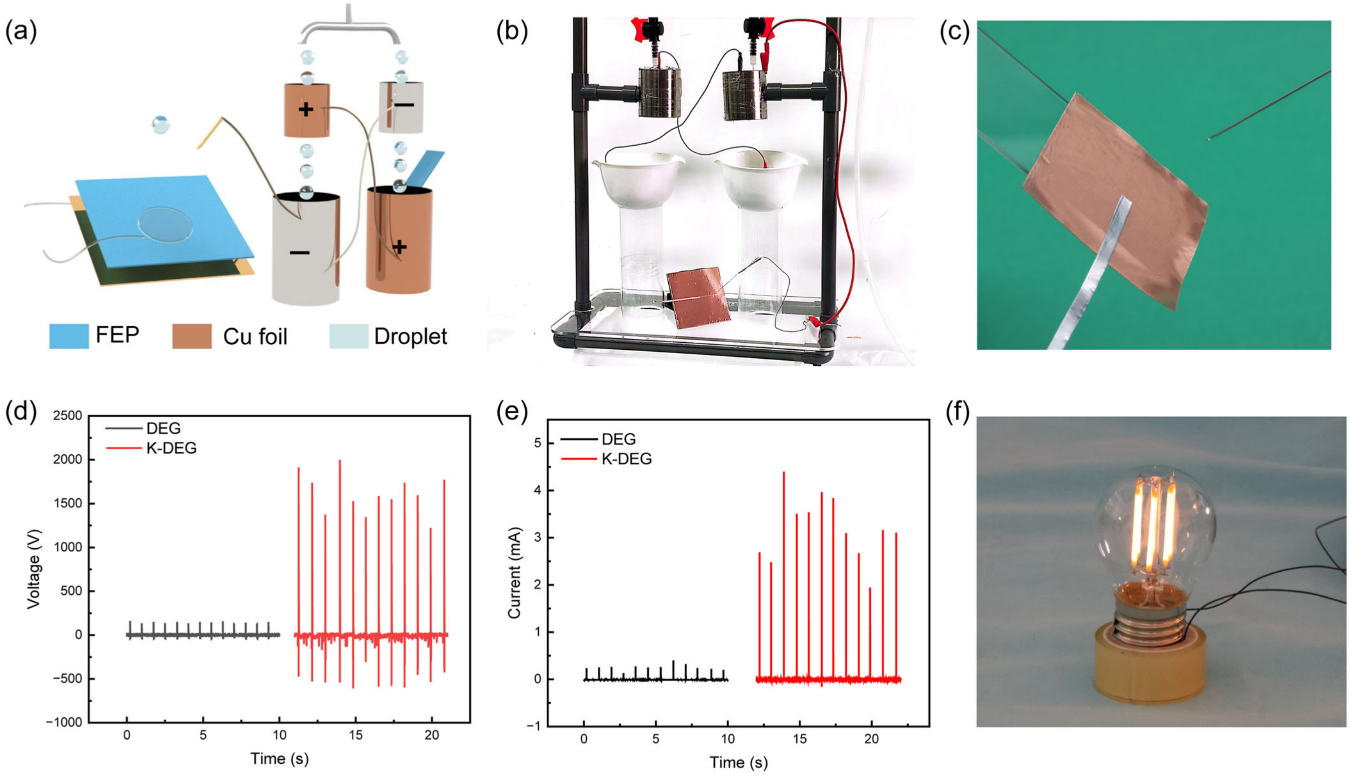

FIGURE 1 Design and performance of the K-DEG. Schematic diagram (a) and optical image (b) of the K-DEG. (c) Magnification photo of a discharging needle placed above the surface of fluorinated ethylene propylene (FEP) film in droplet-based electricity generator (DEG). The comparison of output voltage (d) and current (e) between DEG and K-DEG. (f) A 6-W bulb can be instantaneously lighted by our K-DEG device.

the transferred charge Q_2 is generated from the high-density surface charge and transistor-like architecture of DEG (Figure 2a,iii). As shown in Figure 2e, the Kelvin water dropper injects a large number of charges on the FEP surface during the corona discharge, leading to an ultrahigh surface potential V of −915 V and corresponding surface charge density σ of −358 μC/m^2 at the discharge center. The surface charge density σ can be further increased to −518 μC/m^2 with the increase of charging time until it reaches a saturation state (Figure 2f and Supporting information: Figure S7). Such a high surface charge density of FEP electrostatically induces the same amount of countercharges on the bottom electrode, thereby building a high potential difference across the FEP film. When the impinging droplet touches the top electrode and bridges the originated disconnected FEP and top electrode into a closed loop, a boosted electrical output is driven by the established potential difference across FEP film, resulting in a transferred charge Q_2 (Supporting information: Note 2 and Figure 2a,iii). Moreover, during the cyclic process of droplet impingement and charging by the Kelvin water dropper, the surface charge density of FEP can recover to the initial value of −358 μC/m^2 within the charging time of just 1 s, which indicates that the continuous charging from the Kelvin water dropper can be a robust route to maintain the stability of a high-density surface charge (Figure 2g). The robustness of this charging method from the Kelvin water dropper can also be evidenced by the comparison of output performance between the K-DEG and the DEG that only charged by the Kelvin water dropper for 15 s, in which the K-DEG shows stable electrical output, whereas the output performance of DEG that only charged by the Kelvin water dropper for 15 s significantly degrades under continuous droplet impinging (Supporting information: Figure S8).

To provide further insight into the electricity generation of our K-DEG, we, respectively, treat the Kelvin water dropper that accumulates a large number of charges as capacitor C_{Kelvin} and FEP that carries a high-density surface charge as capacitor C_F in our circuit model (Figure 3a,b). When the spreading droplet touches the top electrode, a closed circuit that consists of four capacitors (C_1, C_2, C_F, and C_{Kelvin}) and three impedances (R_W, R_L, and R_{air}) is formed. In this state, the droplet can serve as a dual switch that not only connects capacitor C_F with an external load but also introduces capacitor C_{Kelvin} into this electrical system, thereby leading to the synergistic charge release from these two capacitors to the external load (Figure 3b). On the basis of the proposed circuit model, the total transferred charge Q of our K-DEG consists of Q_1 resulting from the discharging current of Kelvin water dropper through the droplet channel and Q_2 that originates from the surface charge on the FEP surface in DEG. Therefore, the total transferred charge of this K-DEG can be expressed by the following equation:

$$Q = Q_1 + Q_2. \quad (1)$$

The transferred charge Q_1 resulted from the discharging current from the Kelvin water dropper through the droplet channel can be obtained as follows:

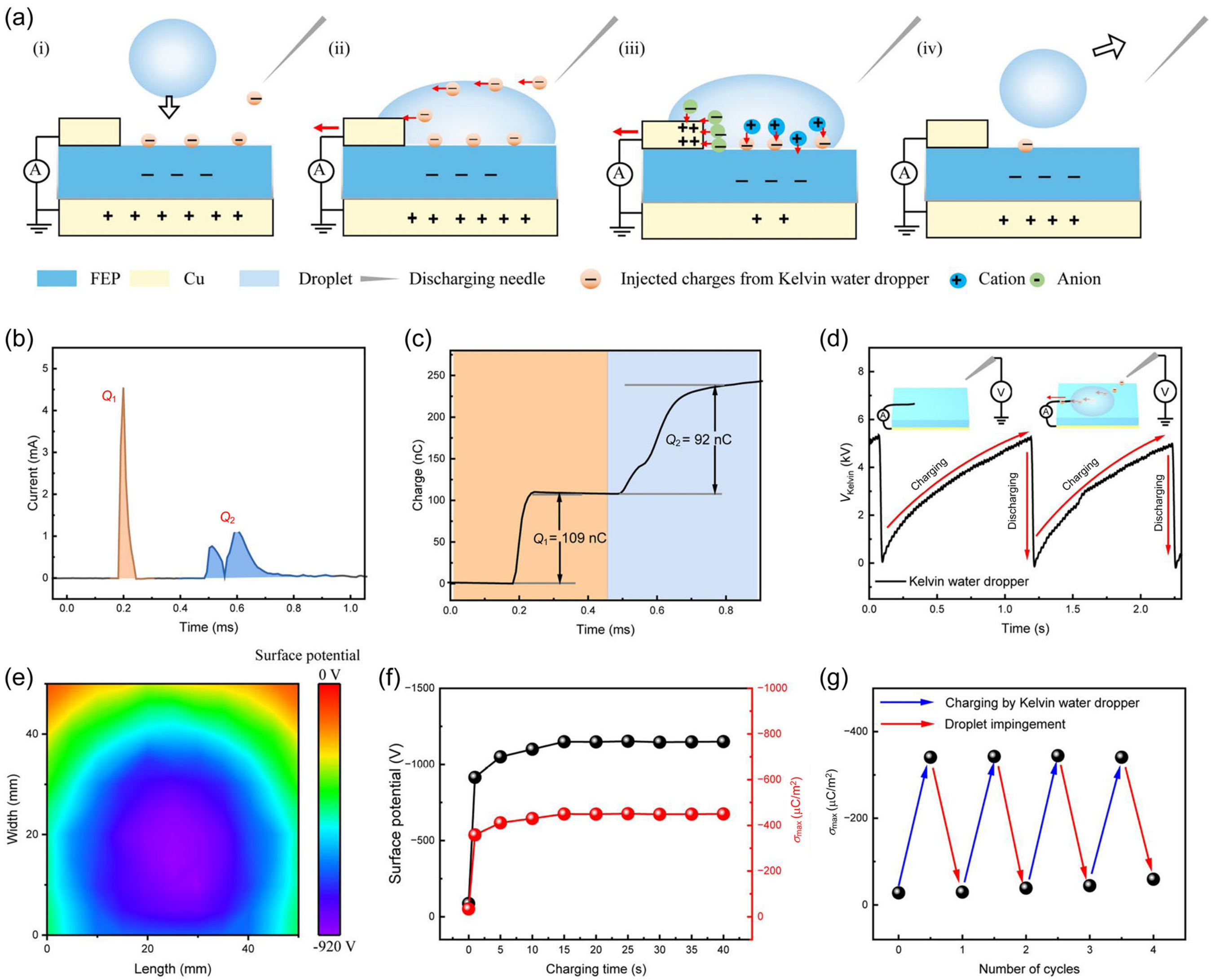

FIGURE 2 Origin of boosted electricity generation. (a) Schematic illustration of the electricity generation of the K-DEG, which consists of the transferred charge Q_1 that resulted from discharging current of Kelvin water dropper and transferred charge Q_2 that originated from preinjected surface charges on fluorinated ethylene propylene (FEP) film. (b) Evidence of two significant peaks of output current that, respectively, associated with transferred charge Q_1 and Q_2 of K-DEG. (c) The measured transferred charge Q_1 and transferred charge Q_2 during one droplet impingement on our K-DEG device. (d) The voltage variation of the Kelvin water dropper during the whole operation of our K-DEG. Before droplet impingement, the voltage of Kelvin water dropper increases rapidly. Upon the droplet impingement, the voltage of the Kelvin water dropper shows a sudden drop and nearly turns to zero, which indicates that the stored charge Q_1 in the Kelvin water dropper is totally delivered into external load through the droplet channel formed between DEG and Kelvin water dropper. (e) The measured surface potential map of the FEP layer in DEG by a customized three-dimensional potential scanner. (f) As continuously charged by Kelvin water dropper, the evolution of surface potential and maximum surface charge density of FEP film of K-DEG with respect to the charging time. (g) During the cyclic process of droplet impingement and charging by the Kelvin water dropper, the surface charge density of FEP film can recover to the initial value before droplet impingement, suggesting the continuous charge injection from the corona discharge of Kelvin water dropper can be a reliable route to maintain the stability of a high-density of surface charge.

$$Q_1 = \int_{t_{on}}^{t_{off}} I_1\, dt = V_{Kelvin} C_{Kelvin}, \quad (2)$$

where V_{Kelvin}, C_{Kelvin}, I_1, t_{on}, and t_{off} are, respectively, the build-up voltage of Kelvin water dropper, the capacitance of capacitor C_{Kelvin}, discharge current, starting time point, and ending time point of discharge current.

Highly depending on the surface charge density of FEP film, the transferred charge Q_2 can be calculated as follows:

$$Q_2 = V_2 C_F = \frac{V_2 \varepsilon_F A_{max}}{d} = \sigma A_{max}, \quad (3)$$

where V_2, C_F, ε_F, d, σ, and A_{max} are the established voltage across capacitor C_F, capacitance of capacitor C_F, dielectric constant of FEP, thickness of FEP, surface charge density of FEP, and maximum spreading area of droplet, respectively.

We next measure the variation of maximum surface potential σ of FEP, and the build-up voltage V_{Kelvin} of the Kelvin water dropper

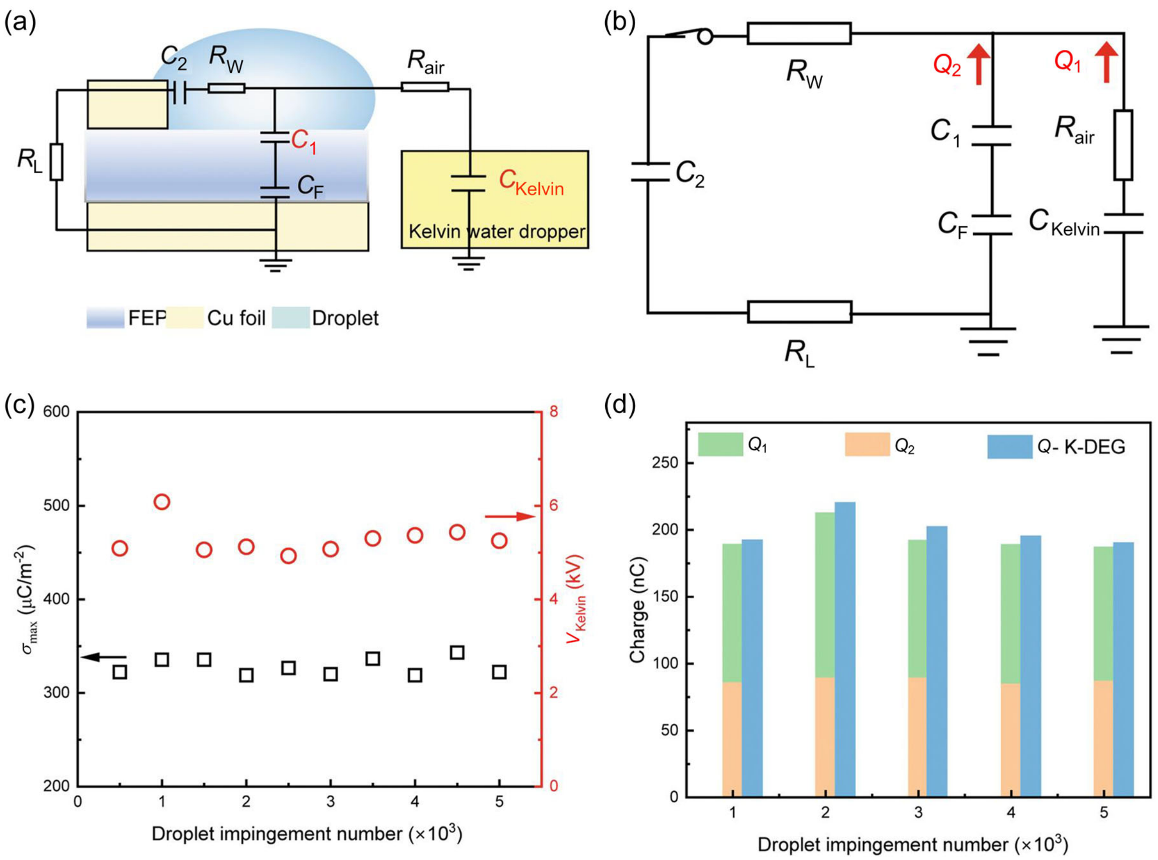

FIGURE 3 Circuit model. (a) Equivalent electronic components and (b) equivalent circuit model of K-DEG before and after charge injection from Kelvin water dropper. (c) The maximum surface charge density and build-up voltage of Kelvin water dropper of K-DEG under continuous droplet impingement. (d) The comparison of transferred charge Q_1, transferred charge Q_2, and total transferred charge Q in K-DEG. FEP, fluorinated ethylene propylene.

during continuous droplet impingement (Figure 3c). The value of the maximum surface potential of FEP is basically in the range of 322–343 μC/m^2, while the built-up voltage of the Kelvin water dropper slightly fluctuates in the range of 5.06–6.08 kV. Based on the measured results of surface potential σ and build-up voltage of Kelvin water dropper V_{Kelvin}, we, respectively, calculate the Q_1 and Q_2 according to the equation: $Q_1 = C_{Kelvin}V_{Kelvin}$, and $Q_2 = \sigma A_{max}$. As shown in Figure 3d, the sum of Q_1 and Q_2 is almost in good agreement with the total charge transfer Q of K-DEG integrated from the output current (Supporting information: Figure S9), suggesting the validation of our proposed circuit model.

Our K-DEG achieves the highest instantaneous output power density of up to 10^5 W/m^2 and output energy density of 1.75 mJ/mL in the field of droplet energy harvesting (Figure 4a),[3,31,40,42] which enables it as a reliable electricity generator for powering commercial electronics, especially the high-power electronics that could not be driven by previously reported DEG with inferior output performance. With such a high output, our K-DEG is capable of driving five commercial 6-W bulbs upon one droplet impingement (100 μL) on our device (Figure 4b and Supporting information: Movie S2). Additionally, 40 LCDs can be directly lighted up by our K-DEG (Figure 4c and Supporting information: Movie S3). In an effort to broaden the practical application of our K-DEG, we adopt a power management circuit to convert the pulse alternating current of our K-DEG into a stable direct current (DC) output. After charging a 100 μF capacitor to a threshold voltage of around 2 V by our K-DEG (Supporting information: Figure S10), we connect the charged capacitor with the DC2048A regulator in the power management circuit to enable a constant voltage output. According to the various demands of different commercial electronics, the DC output of our K-DEG can be switched to different output levels that range from 1.8 to 5 V (Figure 4d). With the combination of K-DEG and a power management circuit, a smartphone can be charged for 5 s by the harvested electricity from a falling droplet (Figure 4e and Supporting information: Movie S4). Note that the capacitor with a larger capacitance to be charged by our K-DEG will prolong the charging time for commercial electronics.

CONCLUSIONS

We develop an efficient and stable droplet energy harvesting device that is characterized by the rational integration of the Kelvin water dropper and DEG with transistor-like architecture. In our design, the

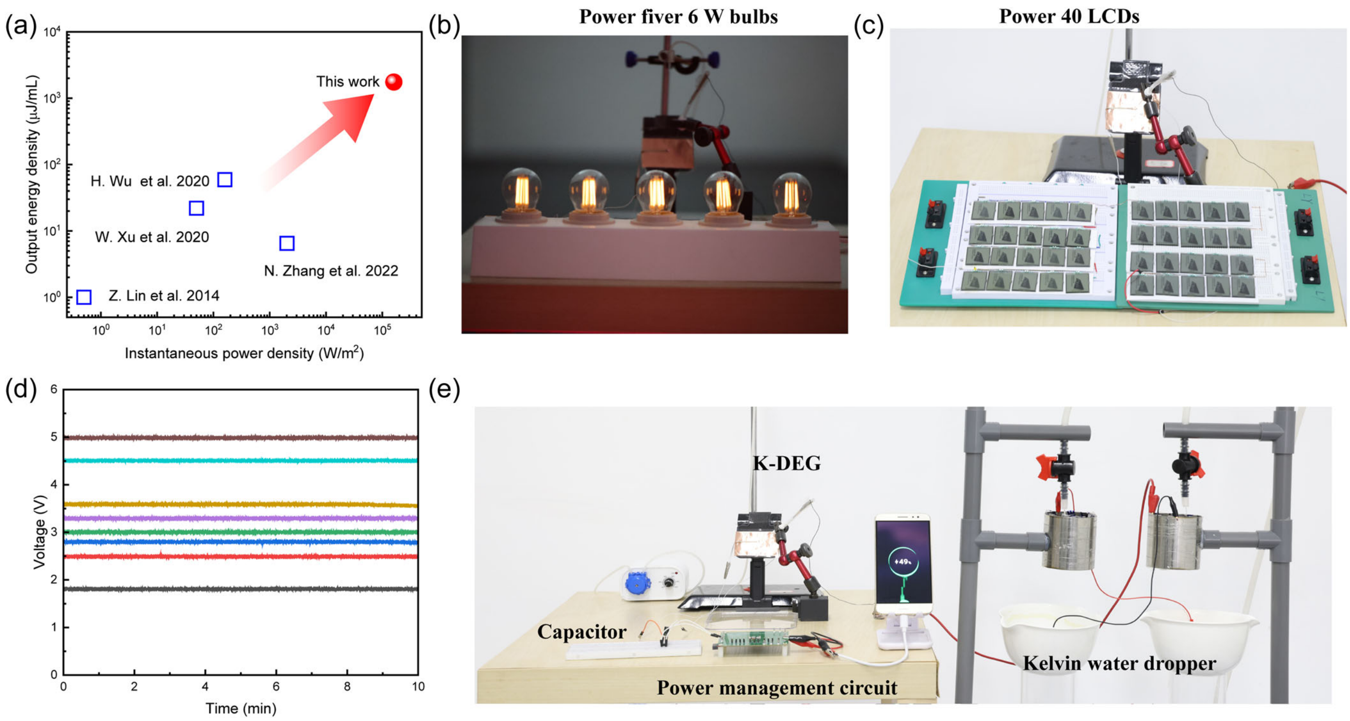

FIGURE 4 Applications. (a) Comparison of instantaneous power density and output energy density of this study (red ball) and the other reported droplet-based electricity generator (blue box). The generated high output power of our K-DEG can be utilized to directly drive (b) five 6-W bulbs and (c) 40 liquid crystal displays (LCDs). (d) The generated direct-current output of our K-DEG is equipped with a power management circuit and can be adjusted into different amplitudes ranging from 1.8 to 5 V according to the various demands of different electrical appliances. (e) A smartphone can be powered by the generated direct-current output from K-DEG.

Kelvin water dropper continuously replenishes a high density of surface charge on the surface of DEG during corona discharge, while DEG with transistor-like architecture can fully release these surface charges into electricity upon droplet impingement. Our K-DEG can achieve a high-density surface charge of 358 μC/m^2 within a short charging time of 1 s, which circumvents the challenge of long precharging time and low surface charge density facing previously reported devices. Moreover, the stability of such a high-density surface charge can be maintained owing to the continuous charge injection from the Kelvin water dropper, which mitigates the disturbing degradation of surface charge density resulting from the inevitable counter-ions adsorption on the charged surface under an aqueous environment. In summary, our K-DEG provides an elegant route to superimpose the DEG with other droplet energy harvesting devices in a linear manner to achieve a dramatically boosted output performance. We anticipate that our K-DEG not only sets a record of high-power DEG but also presents a new way to achieve efficient and stable droplet energy harvesting.

MATERIALS AND METHODS

Acetone (RCL Labscan; 99.5%), ethanol (Sigma-Aldrich; ≥97%), sodium chloride (Sigma-Aldrich; ≥99%), deionized water (resistivity of 18.3 MΩ cm, produced by a deionized water system; DINEC) were used without further purification. Different thicknesses (d = 50, 100, 200, and 500 μm) of transparent FEP films were provided by DuPont de Nemours Inc.

The K-DEG consists of a homemade Kelvin water dropper and DEG that is fabricated by sandwiching a piece of FEP film between the bottom copper electrode and the top copper bar electrode. From top to bottom, the Kelvin water dropper consists of a water container, a couple of faucets connected with plastic pagoda-like connectors that have an inlet diameter of 60 mm and outlet diameter of 1.6 mm, a pair of hollow metal tubes with a diameter of 75 mm and two plastic collecting buckets filled with aluminum foil on their inner wall. The distance between the faucet and metallic hollow tube, neighboring metallic hollow tubes, metallic hollow tube and collecting bucket, and neighboring collecting buckets are spaced at distances of 10, 70, 60, and 20 mm, respectively. Then, the metal tubes and aluminum foils inside the buckets are cross-connected to each other. A piece of FEP film is fixed obliquely above the right bucket of the Kelvin water dropper, which ensures the falling droplets' impact on the surface of this FEP film. After connecting with the right metallic tube of the Kelvin water dropper, a stainless-steel needle (curvature diameter of 20 μm) is placed 5 mm above the surface of the FEP film in DEG.

To control the voltage polarity of each component in the Kelvin water dropper, we fix a piece of FEP film above the right collecting bucket of the Kelvin water dropper to ensure that the feed-in droplets impact this FEP film (Figure 1a). Due to the negative affinity of FEP film, the falling droplets are positively charged by the FEP films, thereby obtaining a positive high-voltage for the right bucket that collects these positively charged droplets. The left metallic hollow tube that is connected with the right buckets is also positively charged. Owing to the electrostatic induction, the left bucket and right metallic hollow tube are negatively charged, respectively. As a result, we can obtain a discharging needle with ultrahigh negative voltage by connecting this discharging needle with the negatively charged left bucket.

The electrical spark that occurs in the Kelvin water dropper is recorded by using a camera (Canon EOS R5). The voltage evolution of the Kelvin water dropper is measured by using the method of connecting a small capacitor (20 pF) in series with the voltmeter (Keithley 6514 in voltage module). The open-circuit voltage of the K-DEG is measured by using an oscilloscope (Rohde & Schwarz RTE 1024) equipped with a high impedance (100 MΩ) probe. The electric current that is lower than 5 mA is measured by using an oscilloscope coupled with a low-noise current preamplifier (Stanford Research System Model SR570) and that for higher than 5 mA is calculated from the voltage across the load resistance measured by using an oscilloscope (Rohde & Schwarz RTE 1024). The transferred charge of the K-DEG upon droplet impinging is measured by a nano coulomb meter (Monroe model 284). For a typical FEP film with a size of 50 mm × 50 mm × 50 µm, the potential distribution map on the FEP surface was measured by a customized 3D electrostatic potential scanner.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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