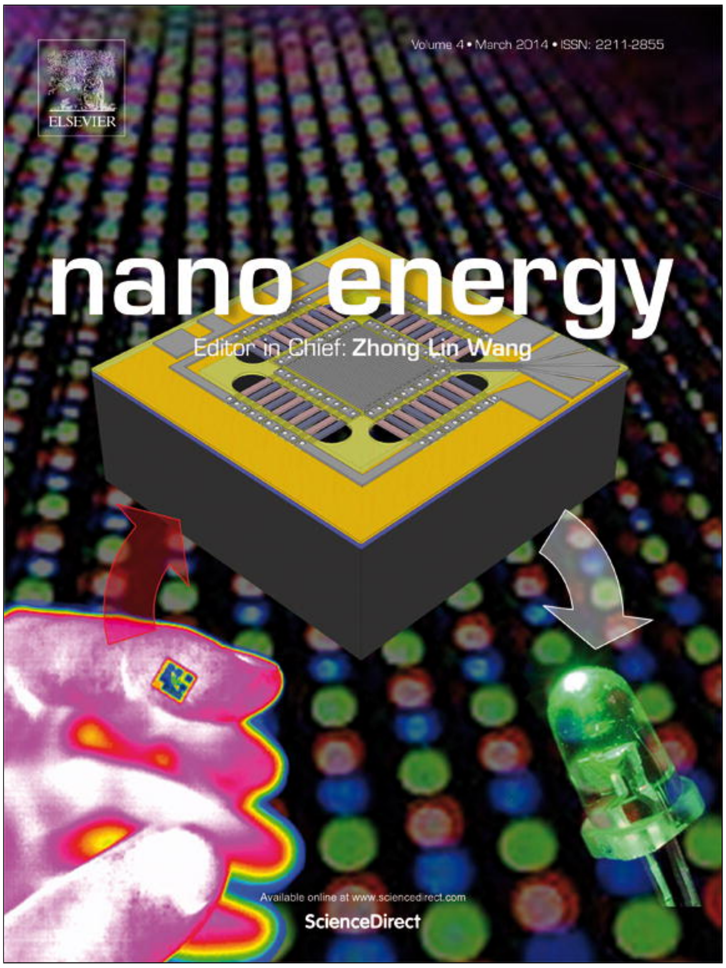
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RAPID COMMUNICATION

Applicability of triboelectric generator over a wide range of temperature

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Abstract
We studied the influence of temperature on the output performance of triboelectric generators (TEGs). PTFE film and aluminum foil are used as the contact materials for the TEG. A high temperature system and a low temperature system were used to conduct measurements of TEG output voltage and current from 300 K to 500 K and from 77 K to 300 K, respectively. Dependence of output performance on temperature was subsequently obtained by statistically analyzing the data as a function of temperature. The performance of the TEG is maximized at around 260 K and degrades at both higher and lower temperatures. A possible mechanism is proposed for explaining the observed phenomenon. Applicability of TEG over a wide range of temperature was confirmed, from as low as 77 K to as high as 500 K, spanning a range of 423 K. Several LEDs connected in series were successfully lit up by TEG as the sole power source at temperatures of 77 K, 300 K and 500 K.

Technological progress in portable electronics, sensor networks, microrobotics etc. significantly changes and improves our quality of living. In the meantime, their mobility, small size and large amount pose serious challenge to the traditional wired power supply. Energy storage devices like batteries and capacitors are the most widely used technologies to meet the demands of these applications [1-4]. However, recharge through traditional power grid is still needed once in a while and this would become very difficult if a large number of such devices are involved. To solve this issue, technologies for in-situ energy harvesting and electricity generation have been widely studied worldwide [5-8] in

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the hope of reducing and eventually eliminating the dependence on traditional power grid.

One recent emerging technology for in-situ energy harvesting comes from a well-known but also unexpected effect: triboelectrification. In this effect, charge separation is achieved through frictional contact between two different materials [9–11]. Often viewed as an adverse effect that may cause fire catching, electrical breakdown or radio communication failure, [12–14] it is only recently seriously considered as a practical option for energy harvesting [15–18] in addition to scientific demonstration [19,20]. This turn of events, however, is very reasonable in the context of the new requirements posed by the miniaturization, portability trend of electronic technology. Ever since its unveil in less than two years ago, the output performance of triboelectric generator (TEG) are dramatically increased to as high as 313 W/m^2 at an estimated efficiency of ~15% [21] and thus demonstrates its great potential of commercial application in the near future. Various questions on how far TEG can go as the solution for in-situ energy harvesting have been asked, including how much more its output power can be enhanced, how small it can be made, how good the durability is etc. It is worth noting that due to its working mechanism, polymer must be at least one of the two contact materials for an efficient TEG [22] and a particular important question concerning this fact is that what is the temperature range that the TEG can work reliably and what are the temperature limits? The objective of this study is to experiment the temperature dependence of the TENG for practical applications.

In this work, simple structured TEGs consisting of PTFE film and aluminum foil as the contact materials are fabricated. TEG output performance from room temperature to 500 K is tested in a chamber equipped with a heater and its output performance from room temperature to 77 K is tested in another chamber equipped with liquid nitrogen cooler. Dependence of output voltage as well as current on temperature is subsequently obtained. Its performance is also tested by powering light emitting diodes (LEDs) at 77 K and 500 K to confirm whether it is still usable under such low and high temperatures.

PTFE film was purchased from DuPont branded as Teflon® PFA that boasts a service temperature from 33 K to 533 K, a melting point of 600 K, a dielectric strength of over 260 kV/mm and great chemical stability. These properties make PTFE film an excellent material for making TEG. The other material was chosen as the aluminum foil due to its excellent conductivity, outstanding thermal and chemical stability (due to its passive oxide layer) and its proven efficiency of electron transfer to polymers like PTFE [23,24]. 2 × 2 in.^{2} of each material are obtained. One side of PTFE film was coated with 200 nm Cu as the electrode and the other side was kept as purchased. Both sides of aluminum foil were kept as purchased, with one side serving as the contact surface and the other side as the electrode surface. Lead wires were attached to the planar electrode surfaces of PTFE and aluminum foil.

TEG performance was firstly tested in the high temperature chamber as shown by Figure 1(a). The chamber was equipped with a heater, a mechanical feedthrough (push rod), several electrical feedthroughs, vacuum ports and a mechanical pump. Aluminum foil was pasted onto a dielectric cast aluminum bracket fixed onto the heater and the PTFE/Cu film was pasted onto another dielectric cast aluminum bracket fixed onto the push rod. Lead wires were connected to measurement systems via electrical feedthroughs and the push rod was attached to a computer programed linear motor that provided an accurate control of position, speed, acceleration etc. for the mechanical stimulation. To effectively maintain the temperature inside, the chamber was isolated from outer atmosphere and to avoid the pressure difference caused by temperature difference, the chamber was constantly pumped down by a mechanical pump. Output voltage was measured when the TEG was connected in parallel to a 5 MΩ load and output current was measured by directly connecting the TEG to a current amplifier. Measurement was done under the temperatures of 300 K, 340 K, 380 K, 420 K, 460 K and 500 K. At each temperature, two hours′ time for thermal equilibrium were allowed before the TEG was tested for 100 cycles to ensure reproducibility. Part of the output voltage data is shown in Figure 2(a) in red curves and part of the output current data is shown in Figure 2(b) in blue curves. The difference between positive voltage/current and negative voltage/current is a result of asymmetry between press and release action but both show a tendency of decrease with increasing temperature. This is especially obvious for the current output at 500 K, where some of the peaks are submerged under noise signals. To more accurately reflect the dependence relationship, 100 cycles of voltage data at

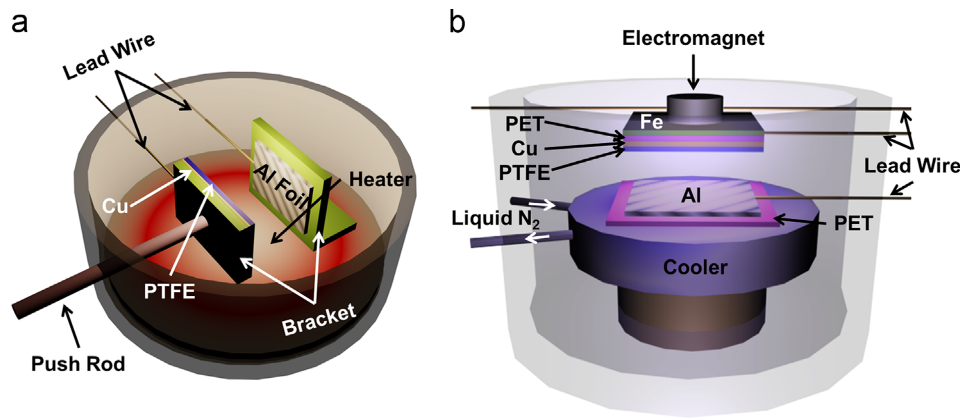

Figure 1 Schematics of the (a) high temperature and (b) low temperature measurement system.

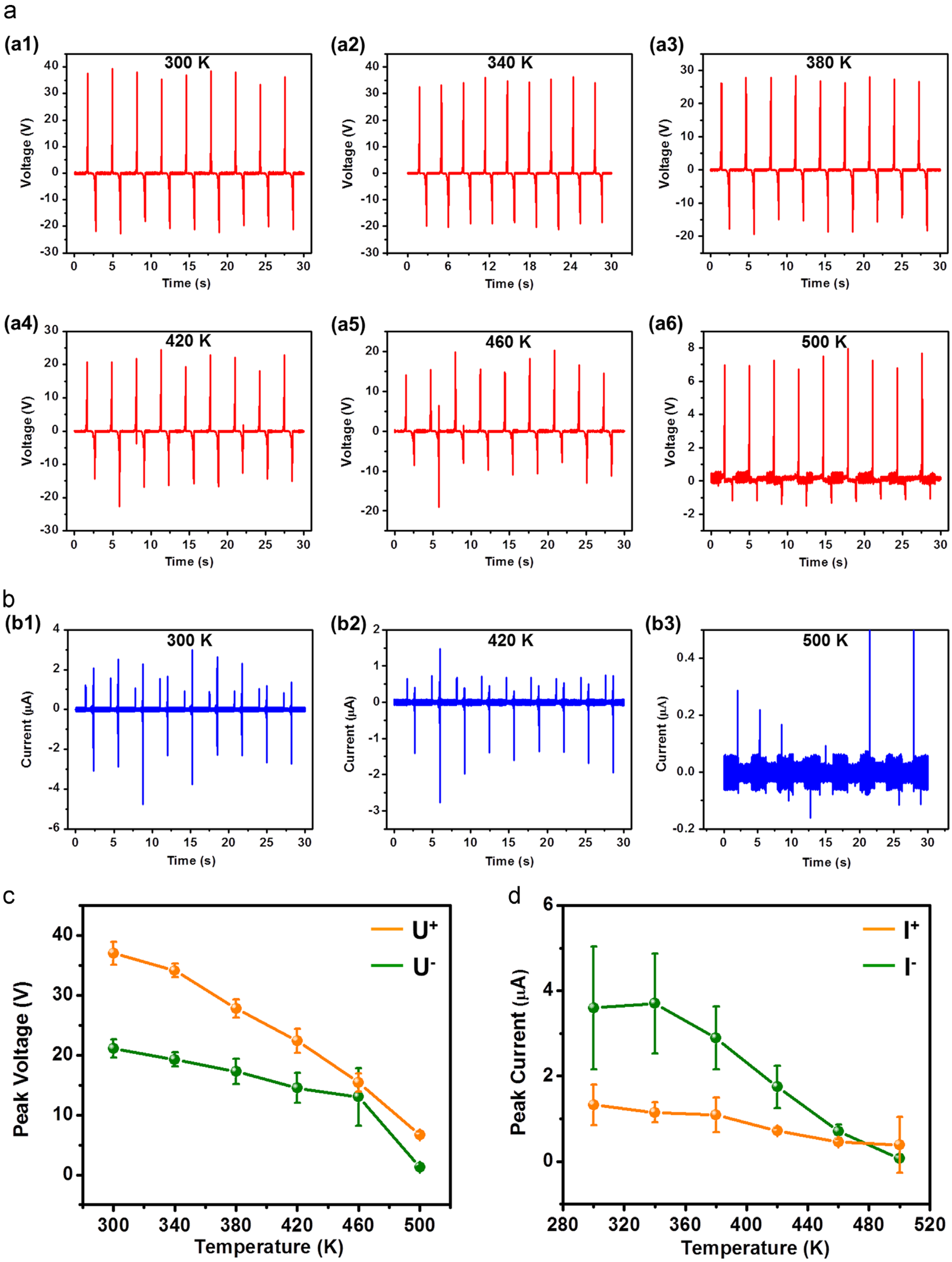

Figure 2 TEG performance from 300 K to 500 K. (a) Output voltage of TEG at (a1) 300 K, (a2) 340 K, (a3) 380 K, (a4) 420 K, (a5) 460 K, (a6) 500 K. (b) Output current of TEG at (b1) 300 K, (b2) 420 K, (b3) 500 K. (c) Dependence of TEG output peak voltage on temperature. (d) Dependence of TEG output peak current on temperature.

each temperature is statistically analyzed and the average peak voltage values and their corresponding standard deviation are plotted against temperature in Figure 2(c), with orange curve representing positive peak values and olive curve representing negative peak values. Similarly, current data at these temperatures are statistically analyzed and the average peak current values and their corresponding standard deviation are plotted against temperature in Figure 2(d), with orange curve representing positive peak values and olive curve representing negative peak values. Both the voltage and current output dependence on temperature indicate that TEG performance tends to degrade at higher temperature. However, on the other hand, it also means that even at a high temperature of 500 K, very close to the stated service temperature limit of 533 K for the PTFE film, the TEG is still able to work, although at a lower efficiency.

The low temperature part of TEG performance is tested in a system schematically shown in Figure 1(b). The chamber was equipped with a liquid nitrogen cooler, an electromagnet, electrical feedthroughs, vacuum ports and a turbo pump. PET film was used to insulate the TEG from the metal stage and the electromagnet. An extra Fe piece was attached to the PTFE/Cu/PET film and mechanical stimulation was achieved by periodically turning on/off the electromagnet so that the PTFE cyclically impacted the underlying aluminum foil. To ensure a uniform magnetic field throughout the experiment under different temperatures, a current meter and an adjustable power source were used to maintain a constant current flow through the coils. Considering that under very low temperatures, material surfaces intensively draws moisture in the atmosphere, the system was constantly pumped down to high vacuum by a turbo pump. The TEG output voltage and current were measured for 100 cycles each, at temperatures of 77 K, 100 K, 140 K, 180 K, 220 K, 260 K, 270 K, 280 K, 290 K and 300 K, with two hours interval between each temperature to ensure thermal equilibrium. Part of the output voltage data is shown in Figure 3(a) in red curves and part of the output current data is shown in Figure 3(b) in blue curves. Average values of positive and negative peak voltages and their corresponding standard deviations are plotted against temperature in Figure 3(c) and similarly the peak current part is plotted in Figure 3(d). From these results, we can conclude that the TEG works reliably under low temperatures. At 77 K, only 44 K higher than the low temperature service limit of PTFE, both its output voltage and current is even higher compared to those under room temperature. With rising temperature up to 260 K, its output gradually increases but the trend is not monotonous and its performance drops quickly when the temperature approaches 300 K.

As is known, there are two important concepts to explain the working mechanism of a TEG [17,22]. One is the triboelectric effect, which means electron transfer occurs between two different materials during the process of mechanical contact/friction. The other is capacitive effect which means when a capacitor has a constant electric quantity Q, the potential difference U between the two plate electrodes is reversely related to the capacitance C or the distance between two plate electrodes. Therefore, when aluminum foil firstly impacts with PTFE, vertical compression leads to lateral expansion, and subsequently leads to relative friction and consequently electron transfer from aluminum to PTFE happens. Static charges on the pristine side of PTFE induces equal amount of charges on the Cu film coated on the other side of PTFE. Since Cu film and aluminum foil form a capacitor, the mechanical energy that drives the cyclic motion of the TEG is partly converted into electricity. In the following impacts between PTFE and aluminum, charge transfer will continue but on both forward (from Al to PTFE due to triboelectrification) and backward (from PTFE to Al due to thermal fluctuation) directions until a dynamic balance is established, leading to a constant charge quantity. Many factors could impact the charge transfer, such as electronegativity of the materials, the area of contact, surface roughness and so on. Among them, thermal fluctuation and the mechanical properties (such as stiffness, ductility) of the material are the two factors closely related to environmental temperature. As is known, thermal fluctuation brings disorder [25]. In this case, it is the driving force for the backward electron transfer from PTFE to aluminum. At very low temperatures, this effect could hardly affect the balance position. With the temperature rising, thermal fluctuation becomes larger, more likely to surpass the barrier height and consequently the backward process overcomes the forward process until a new balance is established, leading to weaker charge separation and smaller output. The other factor, the mechanical properties of the material, affect the effectiveness of friction, which is decided by both the lateral expansion of the material upon impact, related to ductility, and the extent of micro-friction between the rough surfaces of the two materials on the microscale, related to stiffness. Generally speaking, a material becomes stiffer and less ductile at lower temperatures and becomes softer and more ductile at higher temperatures. This means an optimal temperature exists for the most effective friction between aluminum foil and PTFE. From our experimental results, we could see that the output performance of TEG increases from 77 K to around 260 K and then drops monotonously thereafter. This means that the influence of thermal fluctuation is not overwhelming and there is a competing factor from the material's mechanical properties, which leads to the non-monotonic trend of the performance dependence on temperature.

It is worth noting that the output performances of the TEG tested in the high temperature and low temperature systems are different. This is a result of different mechanical stimulation method and chamber configuration. To reflect the overall trend of the 'performance vs temperature', output voltage and current at 300 K tested in the two systems are normalized to 1 and the relative performance change in voltage and current over the temperature range from 77 K to 500 K is reflected in Figure 4(a) and (b). To directly demonstrate its role as a power source, TEG was used to drive several LEDs connected in series (5 mm T-1 3/4 clear LEDs purchased from Microtivity). Firstly, green LEDs were aligned in the shape of letter 'L' and 'T' and were powered by the TEG in the low temperature system. As is shown by Figure 4(c), under both 77 K and 300 K, the 'L' shaped and 'T' shaped LEDs were successfully lit up, by the TEG's positive and negative output respectively. By comparison, the emission intensity for the 77 K case was stronger

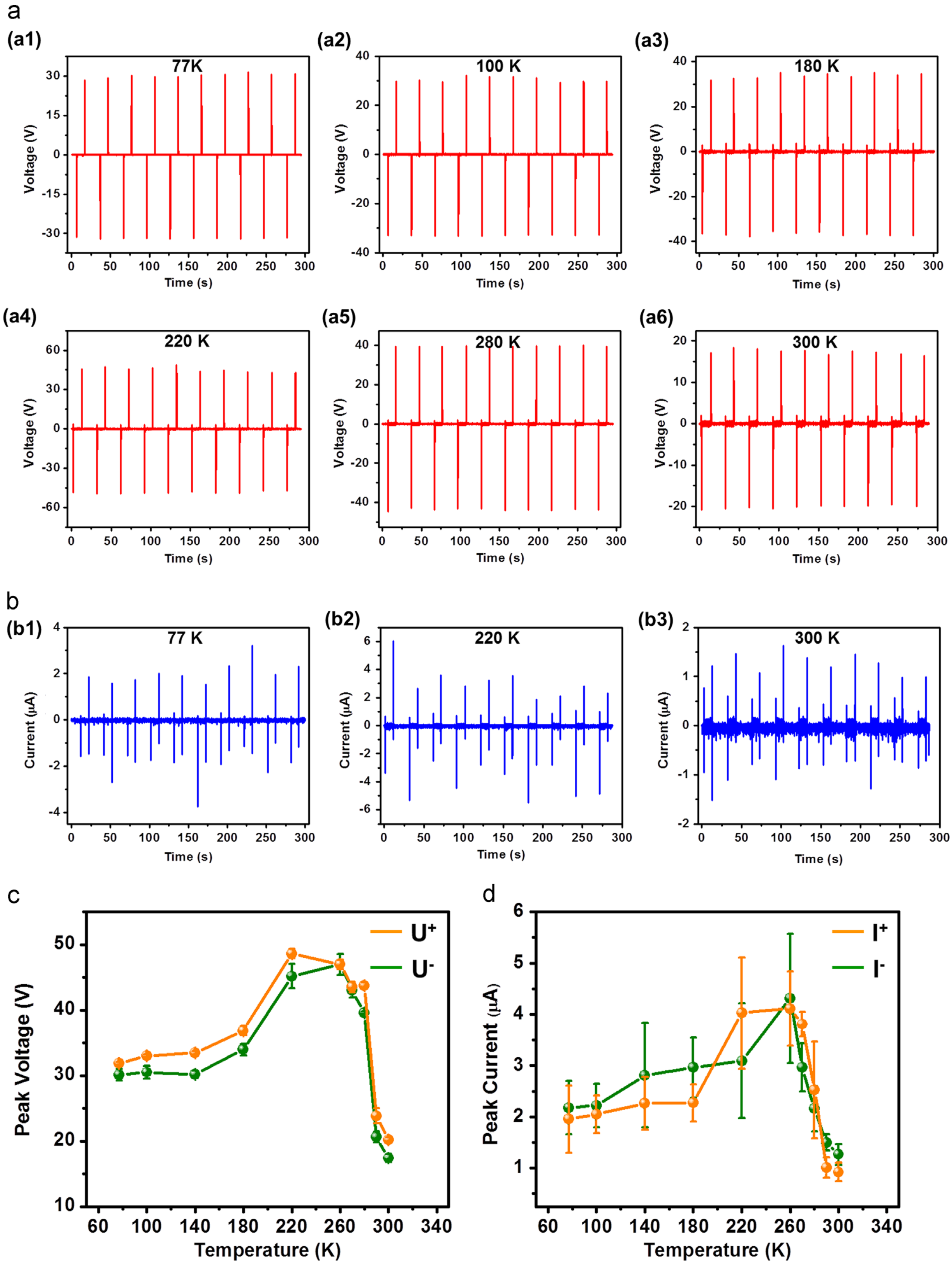

Figure 3 TEG performance from 77 K to 300 K. (a) Output voltage of TEG at (a1) 77 K, (a2) 100 K, (a3) 180 K, (a4) 220 K, (a5) 280 K, (a6) 300 K. (b) Output current of TEG at (b1) 77 K, (b2) 220 K, (b3) 300 K. (c) Dependence of TEG output voltage on temperature. (d) Dependence of TEG output current on temperature.

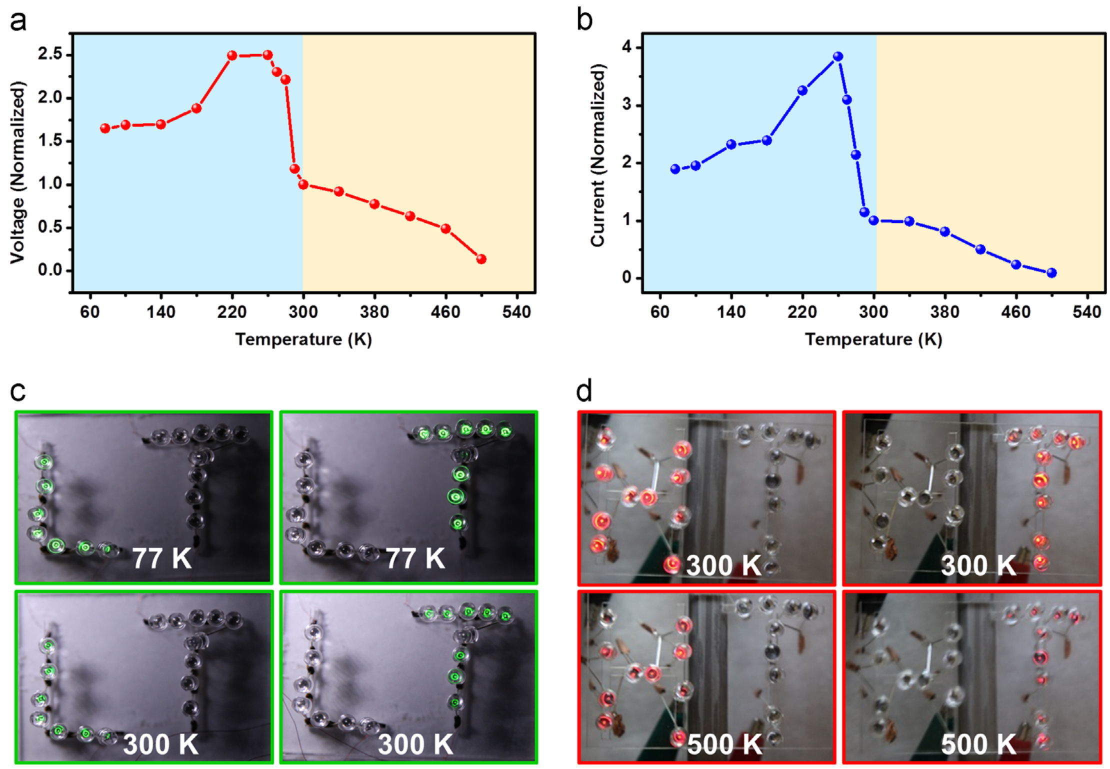

Figure 4 (a) Normalized overall trend of 'output peak voltage vs temperature'. (b) Normalized overall trend of 'output peak current vs temperature'. (c) TEG driving green LEDs at 77 K and 300 K, tested in the low temperature measurement system. (d) TEG driving red LEDs at 300 K and 500 K, tested in the high temperature measurement system.

than that for the 300 K, indicating a higher output for the same TEG at a lower temperature. Similarly, red LEDs were aligned in the shape of letter 'H' and 'T' and were powered by the TEG in the high temperature system. As is shown by Figure 4(d), under both 300 K and 500 K, the 'L' shaped and 'T' shaped LEDs were successfully lit up, by the TEG's positive and negative output respectively. By comparison, the emission intensity at 300 K case is stronger than that at 500 K, indicating a lower output for the same TEG at a higher temperature. The successful lighting up of these LED lights at 77 K, 300 K and 500 K undoubtedly proves the applicability of TEG over such a wide range of temperature and a performance difference is also directly observed by comparing the emission intensity.

In summary, simple structured TEGs consisting of PTFE film and aluminum foil were made to study the temperature effect on its performance. A high temperature system and a low temperature system were used respectively to conduct measurements of TEG output voltage and current from 300 K to 500 K and from 77 K to 300 K. Dependence of output performance on temperature was subsequently obtained by statistically analyzing the data at each temperature point, indicating a tendency of performance enhancement from 77 K to ~260 K and a tendency of performance degradation from ~260 K to 500 K. LED lights were successfully driven by TEG at temperatures as low as 77 K and as high as 500 K. Proper functioning of TEG within such a wide range of temperature meets the demands of most applications in our everyday life and even some special applications in places like the polar regions, ultra-high altitude and alien planet. The results presented in this work adds the confidence of TEG becoming an effective solution to in-situ energy harvesting for a vast variety of situations to support the growing need and rapid progress for tiny, portable and network electronic technologies.

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