

Highly Thermally Conductive Bimorph Structures for Low-Grade Heat Energy Harvester and Energy-Efficient Actuators

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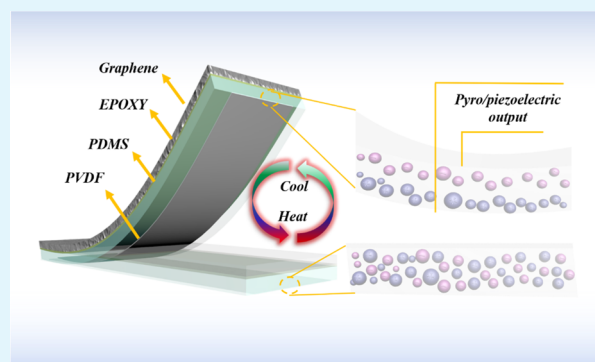
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ABSTRACT: Low-power electronics are urgently needed for various emerging technologies, e.g., actuators as signal transducers and executors. Collecting energy from ubiquitous low-grade heat sources ($T < 100\text{ }^{\circ}\text{C}$) as an uninterrupted power supply for low-power electronics is highly desirable. However, the majority of energy-harvesting systems are not capable of collecting low-grade heat energy in an efficient and constant manner. Limited by materials and driving mode, fabrications of low-power and energy-efficient actuators are still challenging. Here, highly thermally conductive bimorph structures based on graphene/poly(dimethylsiloxane) (PDMS) structures have been fabricated as low-grade heat energy harvesters and energy-efficient actuators. Regular temperature fluctuations on bimorph structures can be controlled by nonequilibrium heat transfer, leading to stable and self-sustained thermomechanical cycles. By coupling ferroelectric poly(vinylidene fluoride) with bimorph structures, uninterrupted thermomechanoelectrical energy conversion has been achieved from the low-grade heat source. Utilizing the rapid thermal transport capability, multifinger soft grippers are assembled with bimorph actuators, demonstrating fast response, large displacement, and adaptive grip when driven by low-temperature heaters.

KEYWORDS: energy harvester, actuators, soft grippers, multilayer, self-sustained thermomechanical



1. INTRODUCTION

Low-power electronics are key components for Internet of things, wearables and healthcare devices, smart homes, and smart cities.^{1–6} For instance, low-power wireless sensors and actuators have been utilized in industries to enable remote or autonomous operation of equipment and control of manufacturing conditions such as temperature and humidity.^{4,5} Most low-power electronics are powered by batteries and the massive use of low-power electronics raises critical issues that the battery replacement becomes very costly when there are thousands of devices in remote locations.^{2,7} Developing new materials,^{8,9} structures, and thus more advanced devices is crucial to continuously improve device performance with lower energy consumption. On the other hand, energy-harvesting systems have emerged as desirable power sources for low-power electronics.^{7,10,11} By collecting ambient energy from surrounding mediums, e.g., sunlight,¹² thermal gradient,^{13,14} vibration,^{3,15,16} and electromagnetic radiofrequency energy,¹⁷ energy-harvesting systems can provide unlimited operation life to low-power devices, eliminating the need to replace batteries.

Energy harvesting from low-temperature heat sources for low-power electronics is highly desirable, as abundant heat sources are widely accessible, e.g., vehicles, manufacturing equipment, geothermal heat, and solar energy.^{13,14,18–21} Thus,

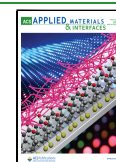
tremendous efforts have been made to develop low-grade heat energy harvesting technologies. Recently, a novel liquid-state thermocell has been investigated to convert low-grade heat energy into electricity using a thermosensitive crystallization process to enhance the Seebeck effect.¹³ Several other systems have also been explored for low-grade heat energy harvesting, including solid-state thermoelectric devices,²² pyroelectric energy harvesting,¹⁴ thermomagnetic process,²³ and thermo-osmotic energy conversion process.²⁴ Typically, large thermal gradients or temperature fluctuations are required for the existing technologies to collect and convert heat energy; however, this cannot be satisfied by heat sources below $100\text{ }^{\circ}\text{C}$.^{14,22,23} Thus, constant and efficient conversion of low-grade heat energy into electrical and mechanical energy still remains challenging.

Meanwhile, actuators have been extensively studied in recent years, aiming to achieve rapid response, low energy

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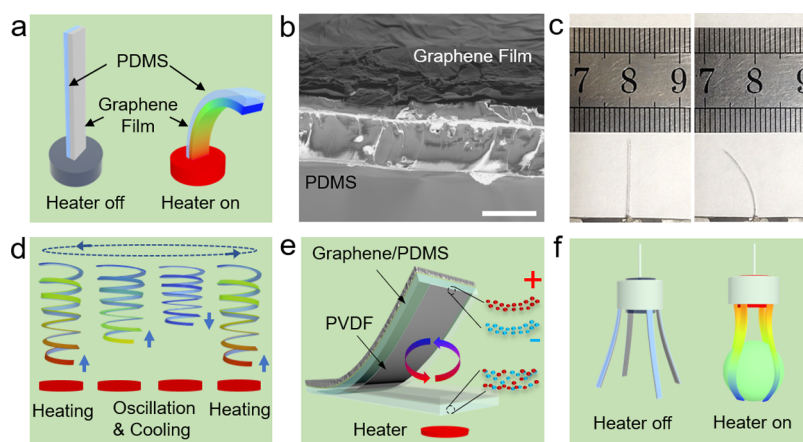


Figure 1. Bimorph structures for low-grade heat energy harvester and soft adaptive actuator. (a) Schematic illustration of the bimorph structure at cooling (left) and heating states (right). (b) Graphene film is attached to a PDMS substrate tightly with the assistance of epoxy glue inside of the actuator. Scale bar is 50 μm . (c) Photographs of the bimorph structure at cooling (right) and heating (left) states. The unit of the ruler is 1 mm. (d–f) Schematic illustrations of a low-grade heat energy harvester and an adaptive gripper ($1.5 \times 10 \text{ mm}^2$). The self-sustained oscillation process of the helical spring contributes to thermomechanical energy conversion (d). The bimorph structure incorporated with piezoelectric PVDF demonstrates constant thermomechanoelectrical energy conversion (e), and a soft gripper adaptively grasps a ball by bending actuators' shape and conforming to the curved shape (f).

consumption, and sophisticated movement.^{14,25–27} Bimorph actuators have received increasing attention due to their ease of fabrication and high energy efficiency with more functional integrations.^{28–33} Electrothermal and photothermal actuators with bimorph structures can be effectively driven by electrical power and light to produce large displacement.^{26,27,34} However, electrical and photo energies are introduced as intermediate energy sources to generate heat for thermomechanical energy conversion, resulting in low response speed and high energy loss.^{26,27,34} Electronic actuators can achieve large strain and quick response, while a major drawback of high driving voltages ($>1 \text{ kV}$) limits their applications.³⁵ Ionic actuators can be driven by a much lower voltage ($<10 \text{ V}$); however, the electrolyte environment is needed for ion transportation.³⁶ Despite significant advancements in materials for the development and functionalization of actuators,^{8,9} more efforts are still needed for the development of low-power, energy-efficient, and fast-responding actuators.

In this work, we have fabricated highly thermally conductive bimorph structures by assembling graphene films and heterogeneous poly(dimethylsiloxane) (PDMS) with drastically different coefficients of thermal expansion (CTE). The bimorph structures demonstrate multiple functions in various application scenarios, including as energy harvester to capture low-grade waste heat energy and convert them into mechanical and electrical energy, as well as soft actuators to grip and move objects. When driven by low-grade heat sources, the bimorph structure establishes a heating–deforming–cooling–recovering–heating loop to collect thermal energy and provide constant mechanical energy output. By further coupling with ferroelectric poly(vinylidene fluoride) (PVDF), the bimorph structure presents the capability to convert low-grade heat energy into electrical energy as a power source for low-power electronics. Meanwhile, benefiting from the high thermal conductivity of graphene/PDMS laminates, the bimorph actuator can be driven by low-temperature heaters below 100°C to generate large displacement with fast response, demonstrating high energy efficiency. We further expand the application of the bimorph actuator as a soft mechanical structure, and the assembled gripper demonstrates the

capability to manipulate objects ten times heavier than itself. The soft feature of the bimorph structure enables grippers to grip objects by conformally adapting their complex shapes, beneficial for picking and placing delicate objects in a safe manner.

2. RESULTS AND DISCUSSION

2.1. Bimorph Structures for Low-Grade Heat Energy Harvesters and Energy-Efficient Actuators. Thermally activated bimorph structures are fabricated by combining highly thermally conductive graphene structures with thin layer poly(dimethylsiloxane) (PDMS) (Figure 1a,b). Graphene belts and films are produced by high-temperature annealing, leading to a dense and well-stacked layer structure with thermal conductivity higher than $1100 \text{ W m}^{-1} \text{ K}^{-1}$.^{37,38} A rough surface has been induced by high-temperature annealing (Supporting Information (SI) Figure S1). However, all functional groups have been removed from the graphene surface during high-temperature annealing, causing challenges for the graphene layer to get a tight bonding with the PDMS layers. Thus, a thin epoxy adhesive layer has been applied to ensure the bonding between graphene and PDMS layers. An enormous mismatch in the CTE exists between graphene materials ($-7 \times 10^{-6}/\text{K}$) and the PDMS layer ($3.1 \times 10^{-4}/\text{K}$), and the temperature rise leads to a large thermal expansion in PDMS and an exceptional bending actuation of the structure (Figure 1c). Low-grade heat energy harvesters have been fabricated based on the bimorph structure with a helical spring shape that can convert heat energy into mechanical energy directly. Helical spring shrinks upon heating and then self-recovers under natural convection cooling and gravitational pulling. Thus, a self-sustained thermomechanical cycling movement has been established to continuously output mechanical energy (Figure 1d). A piezoelectric PVDF film can further be incorporated with the bimorph structure to convert low-grade heat energy into electrical energy as a power source for low-power electronics (Figure 1e). The thermal fluctuation of the energy harvester sustains the cyclic mechanical deformation, and the piezoelectric effect of the PVDF contributes to the continuous electrical energy output. Energy-efficient thermal actuators

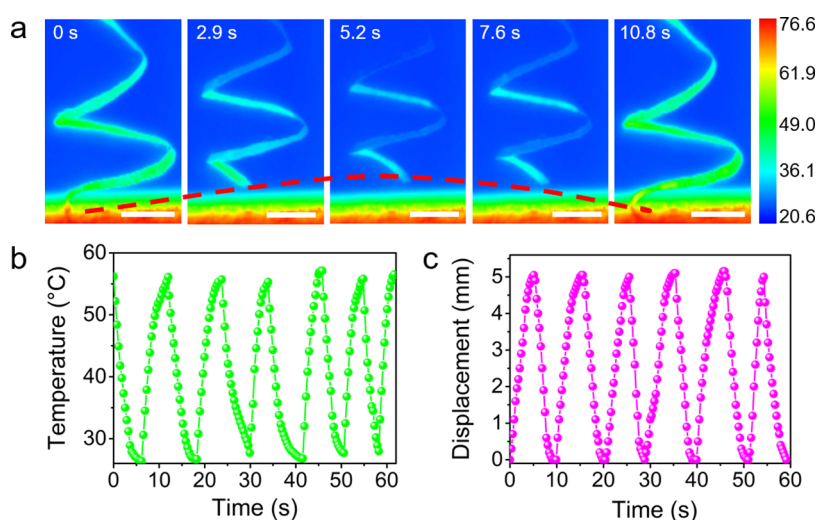


Figure 2. Low-grade heat energy harvesting for mechanical energy output. (a) Infrared images of a helical spring at different times during one oscillation cycle. Scale bar is 1 cm. (b) Transient temperature change of the spring middle point during oscillation cycles. (c) Time-dependent displacement of the spring tip during oscillation cycles.

based on the bimorph structure have further been assembled into multifinger adaptive grippers (Figure 1f). Owing to the rapid heat transport along graphene structures and the flexible graphene/PDMS assembly, the thermal actuator allows large displacement with a rapid response when driven by low-temperature heaters ($T < 100$ °C). An adaptive gripper with multiple soft actuators demonstrates the capability to grip various objects by conformally adapting their complex shapes.

2.2. Conversion of Low-Grade Heat Energy into Mechanical Energy. A helical spring bimorph structure has been fabricated to continuously convert low-grade heat energy into mechanical energy. A self-sustained oscillation movement has been established on a helical spring, and an oscillation movement is initialized when the helical spring tip is heated up by the heat source with a low temperature of 76.6 °C. The absorbed heat energy can be transported rapidly along the graphene layer to heat up the PDMS layer, as indicated by the color change on the spring in infrared images (Figure 2a). Large thermal expansion generated inside the PDMS layer converts heat energy into an upward spinning movement. When the spring tip reaches the maximum height, all of the kinetic energy is converted into potential energy and the first half oscillation cycle is accomplished (see SI, Movie S1). Subsequently, the extra heat from the helical spring dissipated through natural convection and thermal expansion is released. Forced together by gravity pulling, the helical spring spins downward to recover itself and finishes the second half of the oscillation cycle. The transient temperature change of the spring dominated by cyclic heating and natural convection cooling presents persistent and stable periodicity (Figure 2b). With a constant gravitational force, periodic thermal expansion of the helical spring provides an oscillation movement to continuously output mechanical power (Figure 2c).

During oscillation, thermal energy absorbed from heat sources is partially converted into mechanical energy, and the rest is dissipated into the ambience. The helical spring has a long length, and during the short contact with the heat source, transient heat propagation does not reach the top end. When the tip is in touch with the hot surface, convection and irradiation heat loss can be negligible compared to conduction heat harvesting. Thus, we can treat the helical spring as a one-

dimensional semi-infinite solid with a constant heating surface temperature. Due to the low rise in temperature, it is assumed that all properties of materials are temperature independent. The total energy harvested by the tip from the heat source can be obtained as³⁹

$$Q = 2 \left(\frac{K\rho c t}{\pi} \right)^{1/2} (T_s - T_i) S \quad (1)$$

where K is the thermal conductivity of the actuator assembly, ρ is the density, c is the heat capacity, T_s is the surface temperature of the heat source, T_i is the ambient temperature, and S is the contact area between the tip and heat source.

The helical spring has a uniform linear density with a total mass of m and length of L . During oscillation, when the tip rises to a position y from the origin, the total mechanical energy can be written as

$$E = \frac{1}{2}ky^2 + \frac{1}{2}mgy + \frac{m\dot{y}^2}{6} \quad (2)$$

where k is the spring stiffness factor and g is the gravitational acceleration. The first term represents the elastic potential energy of the helical spring, the second term represents gravitational potential energy, and the third term represents kinetic energy. When the helical spring reaches the maximum deformation $y_{\max}$, all of the kinetic energy is transformed into potential energy. The total mechanical energy can be rewritten as

$$E = \frac{1}{2}ky_{\max}^2 + \frac{1}{2}mgy_{\max} \quad (3)$$

Thus, the energy-harvesting efficiency can be obtained by $\eta = E/Q$ (see details in SI Note 1). From eqs 1 and 3, we can see that for a given helical spring assembled by graphene/PDMS layers with constant density, heat capacity, and modulus, the total energy harvested is proportional to $K^{1/2}$ and the mechanical energy output and energy-harvesting efficiency are determined by the spring stiffness factor and maximum deformation $y_{\max}$. To optimize the energy harvester performance, materials with high thermal conductivity and well-designed structures are required. In addition, environmental

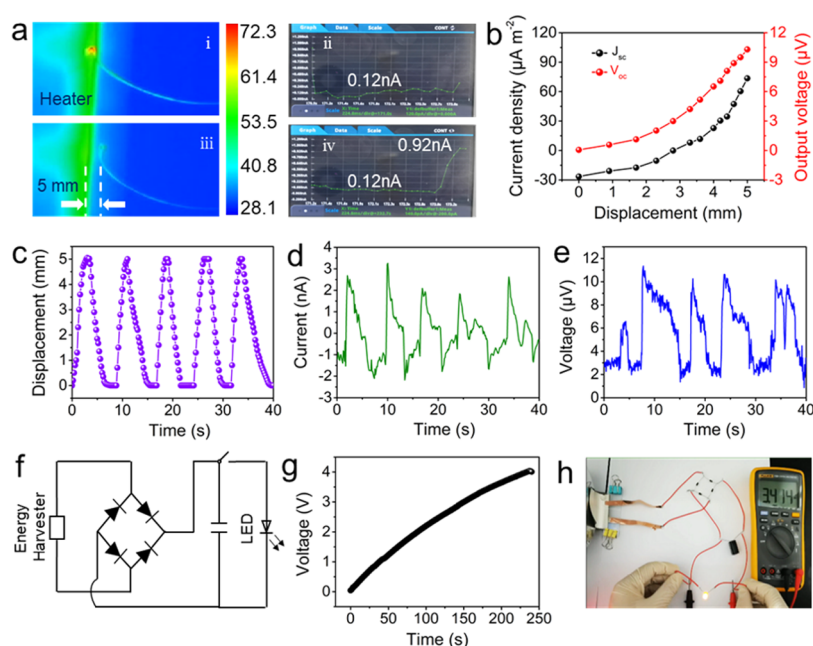


Figure 3. Low-grade heat energy harvesting for electrical energy output. (a) Infrared images of the energy harvester when contacting with the heater (i) and the corresponding transient J_{sc} (ii); the bending movement of the energy harvester (iii) induces a sudden increase in J_{sc} (iv). (b) V_{oc} and J_{sc} increase with the tip displacement of the energy harvester. (c) Time-dependent displacement of the energy harvester tip during cyclic bending motion. (d, e) Periodic J_{sc} (d) and V_{oc} (e) are generated by the energy harvester. (f) Circuit diagram of the energy harvester as a power source for low-power electronics. (g) Energy harvester as a power supply to charge a capacitor. (h) LED bulb powered by the charged capacitor.

variables, including wind and temperature, influence the convection and energy-harvesting process and need to be fully considered during the structure design. The low-grade heat energy harvester with constant mechanical energy output demonstrates great potential as a power source for micro-electromechanical systems (MEMSs) and micro/nanobots.

2.3. Conversion of Low-Grade Heat Energy into Electrical Energy. Bimorph structure is further incorporated with piezoelectric PVDF to convert low-grade heat energy into electrical energy through a cyclic bending motion. A PVDF film with top and bottom electrodes is embedded into the PDMS layer during solidification to construct a graphene/PDMS/PVDF multilayer structure. The bimorph structure in a stripe shape is attached to a metal block as a thermal reservoir with a constant ambient temperature, and the other end is heated by a low-grade heat source with a temperature of 72.3 °C (Figure 3a). Heat energy is collected and rapidly transported along the bimorph stripe. Large deformation generated inside PDMS causes bending movement and mechanical stress on the PVDF film, and the piezoelectric effect shifts positive and negative charge centers towards the top and the bottom of the PVDF film to generate an external electrical field, thus converting mechanical energy into electrical energy (Figure 3a). The open-circuit voltage (V_{oc}) and short-circuit current (J_{sc}) increase correspondingly with the displacement of the energy harvester, clearly demonstrating the thermomechanoelectrical energy conversion process (Figure 3b and SI Movie S2). Upon heating, the bending motion separates the stripe from the heater. Partial collected heat energy is converted into electrical energy and the remaining part is dissipated through natural convection and conduction along the highly thermally conductive graphene layer into the metal block. The bimorph stripe recovers itself to touch with the heater again and a self-sustained cyclic motion is generated (Figure 3c and SI, Movie S3). The cyclic bending

motion of the energy harvester ($1 \times 30 \text{ mm}^2$) induces periodic V_{oc} and J_{sc} with peak voltage and current of 11.3 μV and 3.2 nA, respectively (Figure 3d,e). For practical applications, the low-grade heat energy harvested by the bimorph structure with piezoelectric PVDF can be stored as electrical energy in a capacitor and then used to drive external low-power electronics. Here, a $4 \times 5 \text{ cm}^2$ energy harvester is utilized to charge a commercial 100 nF capacitor and supply electricity to a light-emitting diode (LED). Heat energy is collected from a 100 °C source and peak V_{oc} and J_{sc} of 174 μV and 53 nA are achieved (SI, Figure S2). The AC output generated by the energy harvester is converted to DC signals by a full-wave bridge rectifier circuit to charge the capacitor (Figure 3f,g). After uninterrupted cycles, the capacitor is charged to 4 V (Figure 3g) and the LED can be lit up (Figure 3h). The constant electrical energy output demonstrates the capability of the energy harvester to collect low-grade heat energy as a power source for low-power devices. By fully considering local environmental conditions like wind and temperature, an energy harvester with a more complex structure can be fabricated in the future to further improve the electrical energy output performance.

2.4. Energy-Efficient Bimorph Actuators and Soft Adaptive Gripper. The bimorph structure-based actuators have been further used to build up soft adaptive grippers capable of large displacement with fast response when driven by a low-temperature heater. The bimorph actuator is fixed at one end on a microheater, allowing free movement at the other end without confinement. The large CTE mismatch between the graphene film/belt and PDMS causes the bending actuation of the structure upon temperature rise. When the temperature starts to increase in the actuator, the bending movement occurs synchronously. The bending angle continuously increases to approach the maximum displacement until a steady-state temperature distribution is achieved (see Figure 4a

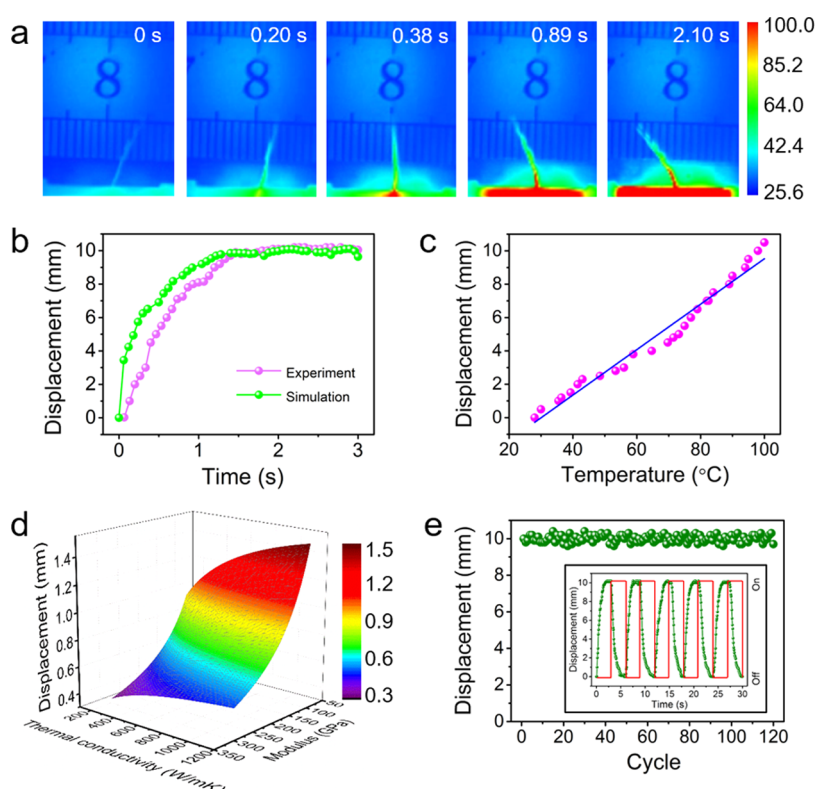


Figure 4. Energy-efficient and fast-responding thermal bimorph actuators. (a) Thermal infrared images of the heated actuator at different durations. The smallest unit of the ruler is 1 mm. The temperature unit is °C. (b) Tip displacement of the actuator with respect to time obtained from experiment and simulation. (c) Tip displacement of the actuator as a function of heating temperature. The blue line is the fitted linear regression curve. (d) Calculated tip displacement of the actuator as a function of graphene belt's thermal conductivity and modulus with heater temperature of 100 °C. (e) Maximum tip displacement during the cycling test. Inset: the transient response of the actuator to the voltage pulse applied on the electrical heater. Pulses of the applied voltage (red line) are superimposed on the displacement.

and SI, [Movie S4](#)). Upon heating at 98 °C, the actuator demonstrates a fast response time of 1.45 s and approaches the final displacement of up to 10 mm ([Figure 4b](#)). The actuation response time is significantly faster than that of the CNT/PDMS structure (30 mm in length) with a response time of 5 s to reach a 9.5 mm maximal displacement.⁴⁰ From room temperature to 100 °C, when normalized to the beam length and temperature rise, the output displacement of the actuator is $0.91 \mu\text{m}/(100 \mu\text{m}\cdot\text{K})$ ([Figure 4c](#)), much greater than that of the current state-of-the-art bimorph thermal actuators, e.g., 0.44 (CNT/PDMS),⁴⁰ 0.15 (CNT/parylene),⁴¹ 0.16 ($\text{VO}_2/\text{SiO}_2/\text{SWNT}$),²⁵ and $0.01 (\text{Si}/\text{SiO}_2)$ ⁴² $\mu\text{m}/(100 \mu\text{m}\cdot\text{K})$. Thus, the bimorph actuator possesses a high energy efficiency to produce mechanical displacement.

The tip displacement of the actuator is determined by graphene and PDMS layer thickness and materials properties. When a 25 μm thick graphene paper was used, the optimized PDMS film thickness was found to be in the range of 50–150 μm for the thermal actuator to achieve maximum tip displacement (SI, [Figure S3](#)). Numerical simulations by combining the heat transfer and thermal expansion process have been carried out to analyze the influences of materials properties on thermal actuation. The actuator in the numerical model experiences the same bending process compared with that from the experiment. The calculated time-dependent tip displacement matches very well with the experimental data ([Figure 4b](#)), validating the accuracy of the numerical model (see SI, [Note S2](#)). Under natural convection, the maximum tip displacement of the actuator increases with the graphene

layer's thermal conductivity due to the higher heat transport efficiency and decreases with the modulus ([Figure 4d](#) and SI, [Figure S4](#)). For various graphene structures, including films, fibers, and belts, thermal conductivity and modulus can be tuned by controlling the internal microstructures and compositions.^{37,38,43} To achieve a large tip displacement, graphene structures with high thermal conductivity and relatively low modulus are desired. This established numerical model can be applied as a guide for designing high-performance actuators.

The fast response of the bimorph actuator can be attributed to the high thermal conductivity of the graphene structure. During actuation, two processes contribute to the response time: (1) the thermal energy transport and (2) the conversion from thermal energy to mechanical energy. For the first process, transient temperature change at the middle point of the actuator is recorded and shows a saturation time of 1.48 s during temperature rise (SI, [Figure S5](#)), consistent with the mechanical actuation response time of 1.45 s. For the second process, the time constant can be characterized by calculating the resonance frequencies of the structure. Given the geometry and mechanical properties of materials, the first resonance frequency of thermal actuators is about 134 Hz (see SI, [Note S3](#) and [Figure S7](#)). As an underdamped system, the response time is estimated within the range of $7.46 \text{ ms} < t < 26.12 \text{ ms}$, much shorter than the mechanical response time of 1.45 s.²⁵ Therefore, the heat transport along the actuator dominates the time response of the whole system, highlighting the importance of using highly thermally conductive graphene

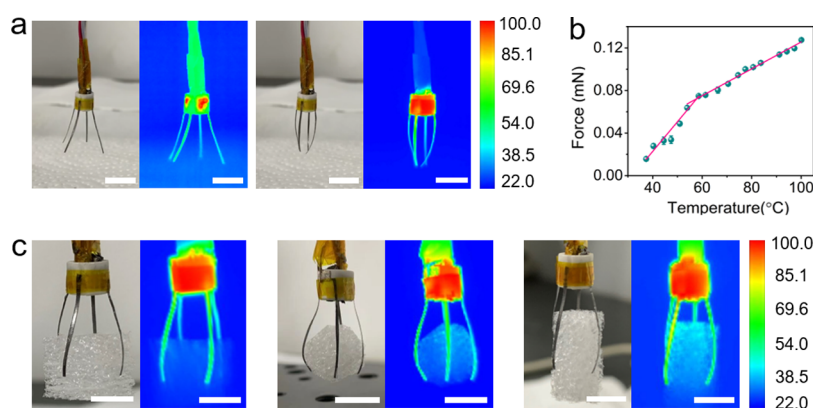


Figure 5. Multifinger adaptive gripper. (a) Optical and infrared images of a four-finger gripper at heater-off (left) and heater-on states (right). (b) Grasp force generated from a single actuator at different heater temperatures. (c) Optical and infrared images of a soft gripper adaptively grasping cubic (left), spherical (middle), and cylindrical blocks (right). Scale bar is 5 mm.

belts for effective heat transport to achieve fast response and high energy efficiency.

The oscillatory movement of the actuator is tested with hundred cycles to demonstrate the high stability of the bimorph structure (Figure 4e). When the structure is driven by an electrical heater with the switching on and off duration of 3 s, the reciprocating motion of the actuator follows the same path without the degradation of the maximum displacement up to a hundred cycles, indicating reversible mechanical actuation and excellent repeatability. The maximum displacement difference rate of the bimorph actuator is only 3.5%. Note our actuators do not show any observable damages after a hundred bending tests. The simple but robust bimorph actuators with long durability in addition to their incredibly fast response and large displacement have great potential in many applications including artificial muscles for microrobots, biomimetic flying, thermal switches, and microsensors.

A four-finger gripper is also assembled with thermal actuators capable of firmly grasping objects of various shapes. After turning on the heater, four actuators are bent easily (Figure 5a and SI, Movies S5 and S6). Grasp force is generated and maintains a high increase rate in the low heating temperature region ($<55^{\circ}\text{C}$). At high heater temperature, radiation heat dissipation from the actuators increases dramatically at the fourth power of the absolute temperature, resulting in a lower force increase rate. The grasp force shows higher linearity with heater temperature, enabling precise control of the output force (Figure 5b). During grasping, the soft bimorph actuators conformally adhere to the surface of cubic, spherical, and cylindrical blocks by adaptively changing their own curves with respect to the external shapes of different objects (Figure 5c and SI, Movies S7 and S8). The adaptive grasp maximizes the contact area, which is beneficial for picking and placing delicate objects with complex geometries and stiffness in a comfortable and safer way.

3. CONCLUSIONS

Low-grade heat energy harvesters and thermal actuators have been fabricated from the highly thermally conductive graphene/PDMS bimorph structures. Energy harvesters with a helical spring geometry are applied to convert thermal energy into mechanical energy. When heated by a low-temperature source, a heating–deforming–cooling–recovering–heating loop is developed to achieve a constant thermomechanical energy conversion. By further coupling the bimorph structure

with a piezoelectric PVDF film, the designed energy harvesters are able to continuously extract thermal energy from low-temperature sources and convert them into electrical energy through self-sustained cyclic locomotion. Moreover, a fast-responding thermal actuator is fabricated with the bimorph structure and shows a large displacement upon heating due to the high thermal conductivity of graphene layers. A multifinger adaptive gripper is assembled with the bimorph actuators, capable of adjusting its own shapes to conformally contact with the object and thus enabling a firm and safe grasp. The simple and robust bimorph structures demonstrate great potential as energy harvesters for low-power electronics and energy-efficient actuators in the field of MEMS, artificial muscle, remote sensors, and switches.

4. EXPERIMENTAL METHODS

4.1. Fabrication of Bimorph Structures for Low-Grade Heat Energy Harvesters and Actuators. PDMS films with a thickness of 50–70 μm were prepared using Sylgard 184 (Dow) by mixing the silicone elastomer base and the curing agent in a mass ratio of 10:1. The mixture was spin-coated on a slide glass and then thermally cured under 80°C for 12 h in a vacuum oven to remove air bubbles. Finally, the PDMS films were peeled off from the slide glass for the fabrication of the bimorph structure. Graphene papers and belts were obtained according to the following references.^{37,38} Thermal conductivities of graphene papers and belts were measured as 1100–1300 $\text{W m}^{-1} \text{K}^{-1}$. A graphene paper/belt was carefully attached to the PDMS thin film with the assistance of epoxy glue to obtain a tight interfacial contact. The graphene/PDMS laminates were cut and rotated into a helical spring structure with a height of 3.5–4 cm. These were applied as low-grade heat energy harvesters for thermomechanical conversion. Poly(vinylidene fluoride) (PVDF), with a thickness of 30 μm , was purchased from Zhimk Technology Co., Ltd. (Shenzhen, China) and cut into strips of $1.0 \times 10 \text{ mm}^2$. A PVDF film with top and bottom electrodes is incorporated with the bimorph structures to convert low-grade heat energy into electrical energy. A single bimorph actuator was fabricated by attaching a graphene belt to the PDMS strip and cut into 10–20 mm in length. An adaptive gripper was assembled by attaching four actuators to a ceramic heater.

4.2. Characterization and Measurement. Thermal videos and images were recorded with a FLIR A615 thermal camera. The cross-sectional SEM images of the bimorph structure were analyzed through a scanning electron microscope (Thermo Scientific, Scios 2). The open-circuit voltage and the short-circuit current were measured using a Keithley 2450 system electrometer (corrected by Keithley 2182A). The tip displacement, V_{oc} , and J_{sc} data were collected independently from an energy harvester with a length of 30 mm and a width of 1 mm, and the heat source temperature was 72.3°C . A large-area

energy harvester ($4 \times 5 \text{ cm}^2$) was utilized to collect thermal energy from a 100°C heat source and charge a commercial 100 nF capacitor (model 104J100, Shenzhen Hongfu Electronic Commerce Co., Ltd.) to light up a LED. Grasp force generated by a $1 \times 10 \text{ mm}$ thermal actuator was measured by a precise analytical balance (Mettler Toledo (ME204TE)), with the measurement accuracy down to 0.1 mg ($9.8 \times 10^{-4} \text{ mN}$). The experimental set can be seen in SI, Figure S6, and the grasp force was obtained by transferring measured weight into force by $F = mg$, in which $g = 9.8 \text{ N/kg}$.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsami.2c08101>.

Infrared video of the oscillation movement of the bimorph helical spring (Movie S1) (MP4)

Cyclic bending motion of the bimorph stripe and the synchronous V_{oc} change (Movie S2) (MP4)

Infrared video of the cyclic bending motion of the energy harvester (Movie S3) (MP4)

Infrared video of the bending movement of the bimorph actuator (Movie S4) (MP4)

Grasping movement of a four-finger gripper (Movie S5) (MP4)

Infrared video of the grasping movement of the four-finger gripper (Movie S6) (MP4)

Soft gripper adaptively grasps a cubic block (Movie S7) (MP4)

Infrared video of the adaptive grasping process (Movie S8) (MP4)

Additional graphite paper photographs, transient temperature changes of the actuator, related calculation details, and simulation analysis (PDF)

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Author Contributions

[†]Z.L. and R.Z. contributed equally. G.W., J.L., and G.X. conceived the project. Z.L. and R.Z. designed and fabricated bimorph structures. Z.L., R.Z., and K.Y. collected and analyzed thermal, mechanical, and electrical data of the low-grade heat energy harvester. Z.L. and Y.Y. characterized bimorph actuators. F.W. and K.L. collected infrared videos of the soft gripper. Z.L. and K.L. carried out simulations. Z.L., R.Z., G.W., J.L., and G.X. contributed to the presentation and writing of the manuscript. All authors discussed the results and commented on the manuscript.

Notes

The authors declare no competing financial interest.

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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