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Self-powered deep brain stimulation via a flexible PIMNT energy harvester

Self-powered deep brain stimulation was demonstrated by a flexible piezoelectric PIMNT energy harvester to induce behavioural change in a living body. The flexible PIMNT harvesting device on thin plastic substrate could be implanted inside restricted space of human body, and generate electricity from cyclic deformations of heart, lung, muscle, and joints to supply electric energy into a deep brain stimulation system in the future.

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Self-powered deep brain stimulation via a flexible PIMNT energy harvester†

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Deep brain stimulation (DBS) is widely used for neural prosthetics and brain–computer interfacing. Thus far in vivo implantation of a battery has been a prerequisite to supply the necessary power. Although flexible energy harvesters have recently emerged as alternatives to batteries, they generate insufficient energy for operating brain stimulation. Herein, we report a high performance flexible piezoelectric energy harvester by enabling self-powered DBS in mice. This device adopts an indium modified crystalline Pb(In1/2Nb1/2)O3–Pb(Mg1/3Nb2/3)O3–PbTiO3 (PIMNT) thin film on a plastic substrate to transform tiny mechanical motions to electricity. With slight bending, it generates an extremely high current reaching 0.57 mA, which satisfies the high threshold current for real-time DBS of the motor cortex and thereby could efficiently induce forearm movements in mice. The PIMNT based flexible energy harvester could open a new avenue for future in vivo healthcare technology using self-powered biomedical devices.

Introduction

Deep brain stimulation (DBS) is a neurosurgical procedure for the stimulation of a specific brain area with electric pulses. 1,2 It is an effective treatment to alleviate various symptoms of neurologic and psychiatric disorders, such as Parkinson’s disease (PD), 3 essential tremor, 4 epilepsy, 5 and major depression. 6 However, the implantable brain stimulator requires repetitive surgeries to replace the battery every 3 to 5 years, a relatively short lifetime due to its high operation power. For example, a commercial brain stimulator (operating at 3–5 V, 130 Hz, and pulse duration of 60 μs) consumes at least a few times higher electric power compared to an artificial cardiac pacemaker (operating at 2 V, 1 Hz, and pulse duration of 400 μs). 7 The frequent invasive medical procedures for replacing batteries involve a risk of inflammation as well as a financial burden to patients. 8,9 A potential solution for addressing this energy issue is to introduce a self-powered...
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Flexible piezoelectric harvesters [called nanogenerators (NGs)] have attracted a great deal of attention for harvesting electricity from ambient mechanical energy including gentle airflow, ocean waves, motor vibration, and even slight movements of human organs/muscles.\(^{12,13}\) Many research teams have studied various piezoelectric materials such as ZnO,\(^{14,15}\) BaTiO\(_3\),\(^{16,17}\) and lead zirconate titanate (PZT)\(^{10,18–20}\) as flexible and self-powered energy sources for implantable biomedical devices.\(^{21}\) Recently, our group demonstrated a self-powered cardiac pacemaker using a flexible single crystalline Pb(Mg\(_{1/3}\)Nb\(_{2/3}\))O\(_3\)–PbTiO\(_3\) (PMN–PT) thin film energy harvester.\(^{22}\) However, the generated energy was not sufficient for the activation of brain neurons in in vivo animal experiments due to a lack of output power. Generally, since the current signals should trigger neural activity that is sufficiently strong to reach the target regions, the current intensity for DBS should be high, in a range of 30–250\(\mu\)A, at resistance from tens to hundreds k\(),\) in previous mouse models.\(^{23–26}\)

It is thus desirable to utilize flexible materials with high piezoelectric properties even in micron-scale thickness to enhance the generated output for self-powered brain stimulators. One such material is single crystalline Pb(In\(_{1/2}\)Nb\(_{1/2}\))O\(_3\)–Pb(Mg\(_{1/3}\)Nb\(_{2/3}\))O\(_3\)–PbTiO\(_3\) (PIN–PMN–PT: PIMNT) which has a remarkable piezoelectric charge coefficient \(d_{33}\) of up to \(\sim 2700\) pC N\(^{-1}\) in a bulk structure.\(^{27}\) In addition to its high piezoelectric properties, the indium modified ternary PIMNT crystal is a 2nd generation relaxor piezoelectric single crystal with a ferroelectric domain size of a few \(\mu\)m, which is much smaller than the 1st generation relaxor-PT crystals such as PMN–PT and Pb(Zn\(_{1/3}\)Nb\(_{2/3}\))O\(_3\)–PbTiO\(_3\) (PIN–PMN–PT: PIMNT) which has a remarkable piezoelectric charge coefficient \(d_{33}\) of up to \(\sim 2700\) pC N\(^{-1}\) in a bulk structure.\(^{27}\) The high piezoelectric properties of PIMNT can be maintained even if the sample thickness is decreased to a micron-scale for flexibility thanks to the unique small ferroelectric domain size.\(^{28}\) In contrast, when the ferroelectric domain size is larger than the thickness of the piezoelectric thin film, the piezoelectric characteristics are significantly degraded by an incomplete ferroelectric domain effect called polarization clamping.\(^{29}\)

Accordingly, it is theoretically predicted that finer domains of single crystal PIMNT thin films could result in improved electric output for flexible energy harvesters compared with other 1st generation piezoelectric single crystals to realize high current driven DBS applications.

Herein, we developed a flexible and high-performance piezoelectric energy harvester enabled by a single crystalline PIMNT thin film on a plastic substrate to demonstrate a self-powered DBS for a live animal. The PIMNT thin film grown using a modified Bridgman method on a bulk wafer was transferred onto a flexible substrate by a stress-controlled nickel exfoliation process without mechanical damages. The PIMNT harvesting device can generate an open-circuit voltage/a short-circuit current of 11 V/285 \(\mu\)A, and \(\sim 45\) \(\mu\)A under a load resistance of 200 k\(),\) which is well matched with load impedance for the electrode of practical DBS, through mechanical bending/unbending motions on a linear stage; these values were sufficient to meet the high standard of brain stimulation. Additionally, an output current of 0.57 mA, corresponding to the highest current signal among flexible piezoelectric NGs, was measured from bending of human fingers. The instantaneous power of the flexible PIMNT device reached 0.7 mW, and could readily charge capacitors and turn on 120 green light emitting diodes (LEDs). Finally, real-time self-powered DBS was accomplished to activate specific neurons using the PIMNT energy harvester in a live mouse. We stimulated the primary motor (M1) cortex to control body movements, and verified that the functional activation of the M1 cortex induced muscle contraction of the forelimb.

**Results and discussion**

**A flexible single crystalline PIMNT film on a plastic substrate and its DBS applications**

Fig. 1a shows the experimental scheme for the stimulation of a particular part of the brain using the flexible PIMNT harvester and an implanted stimulation electrode. The electric energy generated by slight bending motions of the harvesting device is transmitted to the stimulation electrode via metal wires. To confirm the results of brain stimulation, behavioural responses of a mouse can be simultaneously examined by motion capture and tracking. This scheme could be further applied to test the
effect of the stimulation on brain functions such as motor control, cognitive function, and emotional control.

Fig. 1b shows that the flexible metal–insulator–metal (MIM)-type PIMNT harvester bent by human fingers has mechanical durability as well as high flexibility during bending deformation. The flexibility of the energy harvester is not significantly different from a bare PET film as shown in Fig. S1 (see ESI†). A detailed explanation of the device fabrication process is as follows. A PIMNT crystal ingot with rhombohedral composition close to the morphotropic phase boundary (MPB) was grown using the modified Bridgman method, and cut into a polished cuboid with mirror surfaces (crystallographic orientation of isotropic [001]). During the application of the Bridgman method, the indium modified ternary phase contributes to the formation of finer ferroelectric domains in PIMNT crystals. A bottom metal electrode deposited PIMNT block was attached on a silicon substrate using an epoxy adhesive and subsequently thinned to a film with a thickness of ~10 µm by a mechanical grinding followed by a chemical mechanical polishing (CMP) process. After top metal electrode deposition, an electric field of 1 kV mm\(^{-1}\) was applied to the PIMNT thin film to align the internal dipoles.

A stress-controlled exfoliation process was utilized to detach the top MIM layer (area of 1.7 cm \(\times\) 1.7 cm) from the substrate by a tensile nickel layer formed by electroplating. This mechanical exfoliation method could offer a quick, simple, cost-effective, and safe transfer process for demonstration of a flexible energy harvester compared to selective chemical etching or dissolution.16

The directional stress mismatch between the tensile-stressed nickel film and a compressive-stressed PIMNT MIM layer induced spontaneous exfoliation of the entire piezoelectric film from the mother wafer without mechanical damage.30,31 The freestanding nickel/MIM structure was bonded onto a polyethylene terephthalate (PET) substrate (125 µm in thickness), and the nickel film was removed by wet etching. Finally, copper wires were linked to the top and bottom electrodes of the PIMNT MIM structure to complete the fabrication of the flexible energy harvester. The finished flexible piezoelectric harvester is advantageous to generate electricity by a small force (or a slight movement) compared to its original state (PIMNT film on rigid silicon substrate), since the bending stiffness of the PIMNT film on the plastic substrate is much smaller than the same thickness of the PIMNT film on the mother silicon substrate (Fig. S1 in ESI†).32

Fig. 1c shows a cross-sectional scanning electron microscopy (SEM) image of a flexible PIMNT film on a PET substrate. The PIMNT film was located on a polyurethane adhesive layer without delamination or cracking of the piezoelectric material. The inset of Fig. 1c presents X-ray diffraction (XRD) results of a single crystalline PIMNT with only the (001) crystallographic direction. Fig. 1d shows Raman spectroscopy to analyse the phase of the PIMNT material using a 514.5 nm Ar\(^+\) laser as an excitation source. The modes at around 120 cm\(^{-1}\), 270 cm\(^{-1}\), 435 cm\(^{-1}\), 570 cm\(^{-1}\), 737 cm\(^{-1}\), and 790 cm\(^{-1}\) in the spectra indicate that the single crystalline PIMNT film has typical features of a perovskite PT-based relaxor.33 According to previous reports on PMN–PT and PMN–PbZrO\(_3\)–PT (PMN–PZT), the broadened \(A_{1g}\) mode consists of two Raman peaks at around 740 cm\(^{-1}\) of tetragonal symmetry and 800 cm\(^{-1}\) of rhombohedral symmetry.34,35 The \(A_{1g}\) mode that results from the PIMNT film with the coexistence of 737 cm\(^{-1}\) and 790 cm\(^{-1}\) is attributed to the composition of the PIMNT crystal being located near the MPB with the main rhombohedral phase and the trace microscopic tetragonal phase. Fig. 1e shows the compositional characteristics of the top surface of the PIMNT film on a flexible substrate obtained from an energy dispersive spectroscopy (EDS) analysis. The composition of the flexible PIMNT film was also investigated by X-ray photoelectron spectroscopy (XPS) analysis, as shown in Fig. 1f. These results clearly indicate that the flexible single crystalline PIMNT on the PET substrate incorporates all required elements, such as Pb, In, Nb, Mg, Ti, and O constituents, in the measured areas.

**Dielectric properties and simulation results of the flexible PIMNT film**

Fig. 2a presents the dielectric properties of the PIMNT MIM structure on the plastic substrate to verify that the ferroelectric characteristic is maintained after the stress-controlled exfoliation process. The dielectric properties of the PIMNT film, with top and bottom electrodes (area of 300 µm \(\times\) 300 µm) as shown in the inset of Fig. 2a, were measured at room temperature as a function of frequency (ranging from 3 kHz to 1 MHz) at a constant oscillation frequency of 1 kHz. The dielectric constant and loss of PIMNT MIM on a plastic substrate as a function of frequency from 3 kHz to 1 MHz. The inset shows a top view OM image of tetragonal top electrodes for the dielectric characterization. (a) The theoretical simulation model of an MIM-type PIMNT thin film energy harvester, and the piezopotential distribution inside the PIMNT harvesting device under a tensile strain of 0.3%.
voltage of 5 mV_p-p. The dielectric constant and dielectric loss tangent δ were above 1130 and below 0.08, respectively, in the analysed frequency range.

Fig. 2b and Fig. S2 in ESI† show the theoretical simulation model of the piezopotential distribution inside the MIM-based PIMNT energy harvester calculated by a finite element analysis (FEA) using multiphysics COMSOL to provide the working principle and estimation of the output voltage from the flexible harvesting devices. We simulated a simplified model composed of a piezoelectric PIMNT thin film layer (10 μm in thickness, a piezoelectric voltage constant of g_{31} = −18.3 × 10^{-3} V m N^{-1}, Young’s modulus of E = 15 GPa, a dielectric constant of K^T = 4400, and a mass density of 8150 kg m^{-3}) on a PET substrate (125 μm in thickness) with a curvature radius of 20.5 mm (tensile strain of 0.3% at the top PET surface) to predict the output voltage of the flexible PIMNT harvester.\textsuperscript{36,37} For the estimation of device performance, the PET substrate is extended in the parallel direction for 0.3% of the total film length in the theoretical FEA model. From the relationship ε = ΔX/X_0 between the tensile strain (ε_p) and the initial width (X_0) of the PET film, the plastic substrate is elongated for a displacement (ΔX) of 120 μm in the FEA model. We assumed that no failure modes such as delamination, slipping, or cracking of the piezoelectric thin film on the PET substrate were considered in the theoretical simulation.\textsuperscript{36,37} As illustrated in the inset of Fig. 2b, the PIMNT thin film on the plastic substrate has a piezopotential difference (ΔV) of 24.5 V between the neighbouring top and bottom electrodes upon mechanical deformation; this computational simulation is basically defined by ΔV = g_{31} l ε_p E, where ΔV is the output voltage of the PIMNT material, g_{31} is the piezoelectric voltage constant, l is the perpendicular distance between the adjacent MIM electrodes, ε_p is the tensile strain applied on the PIMNT film, and E is Young’s modulus of the PIMNT.\textsuperscript{38} This simulation result verifies that the bending motion of the flexible PIMNT harvesting device can be converted into a high output voltage.

Output performance of the flexible PIMNT energy harvester

To measure the electric output signals from the flexible PIMNT thin film energy harvester, we used a linear bending stage, a source-meter, and a Faraday cage. During the investigation, periodic mechanical bending and unbending motions (Fig. 3a) were applied to the harvester on the bending stage with a slight horizontal displacement of 2.85 mm from an original 4 cm long sample, a strain of 0.3%, a straining rate of 2.3% s\textsuperscript{-1}, and a frequency of 0.32 Hz. Fig. 3b-i and -ii show the characterization result of the PIMNT energy harvester in the forwardly connected state (the inset of Fig. 3b-i), where the maximum open-circuit voltage and short-circuit current were 11 V and 283 μA, respectively, which generated four times higher output power than the PMN–PT harvester (corresponding output voltage of 8.3 V and output current of 145 μA by a bending motion).\textsuperscript{22} Furthermore, a maximum current signal of 0.57 mA was obtained from the bending of a flexible PIMNT harvesting device using human fingers (Fig. S3 in ESI†). The exceptionally high piezoelectric performance of the PIMNT film even in 10 μm in thickness can be explained by the relatively small ferroelectric domain size (a few μm) of 2nd generation ternary PIMNT crystals.\textsuperscript{29,41} Piezoelectric single crystals with small domains are advantageous for micron-scale thin films in terms of maintaining their high piezoelectric constants, compared to binary phase 1st generation relaxor-PT crystals with large domain sizes (10–50 μm) as we aforementioned. On the micro-scale level, poling along the ⟨001⟩ direction in rhombohedral-based relaxor-PT crystals produces four domain variants, and the dipoles in domains can be aligned along any one of the four equivalent (111) directions. When the physical thickness of the piezoelectric crystal is much larger than the domain dimension, the four domain types can be evenly populated and form stable multi-domain structures, corresponding to a simple polarization rotation, which provides a large d_{33} value in relaxor-PT single crystals. In contrast, when the thickness dimension of the piezoelectric single crystal becomes smaller than the ferroelectric domain size, the surface boundary conditions may impede the equilibrium of multi-domain
configuration and polarization rotation (i.e., domain clamping effect), causing a serious decrease of the piezoelectric charge coefficient. Therefore, our ternary PIMNT thin film with a thickness of \(\sim 10 \mu m\) allows a high \(d_{33}\) value on a flexible substrate, whereas the binary relaxor-PT thin films have a severely degraded piezoelectric charge constant.

A switching polarity test was conducted to establish that the measured pulses were indeed harvested from the piezoelectric effect of the PIMNT thin film.\(^{42}\) When a reversely connected state was established between the energy harvester and the measuring unit, the flexible NG device successfully generated a negative voltage and current peaks on the bending states (Fig. 3c-i and -ii). A bending fatigue test was also performed to verify the mechanical endurance of the flexible harvesting device. As presented in Fig. 3d, the output current signals were steadily observed without a notable change during ~15,000 bending and unbending cycles at a bending radius of 20.5 mm. The outstanding stability of the piezoelectric NG was attributed to the robust characteristics of the flexible PIMNT thin film under significant periodic deformations.\(^{43}\)

### Output power and applications for consumer electronics of a flexible PIMNT harvesting device

We also investigated the voltage and current signals from the flexible energy harvester with external load resistors varying from 120 \(\Omega\) to 220 \(\Omega\) to characterize the effective instantaneous power outputs of the flexible energy harvester, as shown in Fig. 4a and b. The instantaneous output power as a function of the resistive loads was calculated by multiplying the maximum output voltage and current values.\(^{18}\) The output voltage signals steadily built up as the load resistance increased and became saturated at a high resistance (> 10 \(\Omega\)), while the sustained high output current signals at a low resistance gradually decreased with an increase of resistance. From the results, we obtained a maximum instantaneous power of 0.7 mW (multiplication of 7 V and 100 \(\mu\)A) when driving under a load resistance of 70 K\(\Omega\); this satisfies the standard criteria for electric stimulation of neural tissues in an animal brain. To use the flexible PIMNT harvester as a supplementary energy source of a brain stimulator, it is essential to store the electric energy generated by the mechanically deformed harvesting device.\(^{44,45}\) Generally, flexible piezoelectric energy harvesters generate alternating current (AC) pulses, which cannot be directly utilized to drive direct current (DC) systems of conventional DBS devices. The AC signals accordingly are converted into DC outputs using a full bridge-rectifying circuit consisting of four commercial diodes.\(^{46}\) The rectifying output current signals reached ~220 \(\mu\)A by cyclic bending motions, as shown in Fig. S5 (see ESI†). These output pulses were used to charge various sized capacitors and operate commercial electronics. Fig. 4c shows the charging curves of four different capacitors (capacitance of 33 \(\mu\)F, 68 \(\mu\)F, 220 \(\mu\)F, and 470 \(\mu\)F, respectively) by continual bending of the harvesting device (an induced strain of 0.3%, a strain rate of 2.32% s\(^{-1}\), and a frequency of 0.32 Hz). These capacitors were charged by the flexible PIMNT thin film harvester from 0 V to 2 V within tens to hundreds seconds (15 s for 33 \(\mu\)F, 27 s for 68 \(\mu\)F, 91 s for 220 \(\mu\)F, and 193 s for 470 \(\mu\)F, respectively). The energy conversion efficiency between the energy harvesters and the storage elements could be increased by adopting advanced power conversion circuits such as a bias-flip rectifier, a reconfigurable capacitor array, and a flyback DC/DC converter.\(^{47}\)

Moreover, as shown in Fig. 4d, the rectified electric output of the PIMNT energy harvester was capable of directly turning on 120 parallel connected green LEDs (see Video S1 in ESI†) with momentary bending/unbending motions. The relatively high current output from the energy device is advantageous for operating a bundle of LEDs in parallel. These results indicate that the flexible PIMNT thin film harvester on a single plastic substrate provides an innovative means of assuring longer working hours of implantable DBS systems, particularly in the small spaces inside the human body, because the thin film energy harvester can charge a depleted battery by responding to slight mechanical movements of human organs such as the heart, lungs, and diaphragm.\(^{48}\)

### Self-powered DBS via the flexible PIMNT harvester

The effective electric stimulations activate the brain neurons, which can mediate relevant behaviours of the living body. Herein, we stimulated a mouse brain using the self-powered energy of the flexible PIMNT thin film harvester without any other external energy source. To determine the effect of stimulation, we targeted the M1 cortex in the brain, whose role is to generate muscle contraction of the forelimbs.\(^{26}\) Fig. 5a presents the experimental scheme using the mouse and a simplified illustration of the neural pathway responsible for the movement of the right forelimb. The stimulation electrode was localized on the
Multilayer stacking of piezoelectric thin films on a single flexible energy device could be increased by introducing three-dimensional current for neuron activation. The electrical output from the flexible PIMNT harvesting device in Fig. 5e, and the right paw of the mouse was moved about 1.3–2.3 mm by the generated stimulation electricity at each device bending state. In general, the current should be above 30 μA to cause contractions of the forelimb muscles for electric stimulation of the mouse M1 cortex. Considering the impedance of the simulation electrode (∼200 kΩ) in our experiment, the current generated in this scheme was ∼45 μA (calculated from the data in Fig. 4a), thus exceeding the threshold current for neuron activation. The electric output of the flexible energy device could be increased by introducing three-dimensional multilayer stacking of piezoelectric thin films on a single flexible substrate. Although the price of the flexible single crystalline PIMNT harvester is higher than other polycrystalline piezoelectric materials, we believe that the removal of the operation procedure for replacing the depleted batteries in DBS could compensate the device cost issue, which is relatively low compared to the entire operation. Our experimental results indicate that the flexible PIMNT energy harvester can generate functional neural signals in the brain in vivo.

Conclusions

In summary, a flexible single crystal PIMNT thin film harvester was successfully developed and utilized for self-powered DBS to induce body movements of a live animal. The flexible piezoelectric PIMNT harvesting device on a single PET substrate converted a maximum output current of 0.57 mA and a voltage of 11 V from mechanical deformation and biomechanical motion, respectively. The outstanding output performance of the PIMNT energy harvester is attributed to the relatively small ferroelectric domain size of the ternary PIMNT crystal thin film, which enables a high piezoelectric constant on the plastic substrate. The harvested electricity directly stimulated a certain area of the animal brain to induce corresponding body movements. We verified that the functional activation of the M1 cortex of a living mouse via the flexible harvester generated immediate bending motions of the right forelimb. This indicates that the flexible PIMNT energy harvester can be used for a self-powered DBS device to supply electric power or recharge internal batteries. Further applications are possible using its characteristics, such as a motion-feedback neuronal stimulator similar to an artificial sensory system, and a tremor intensity sensor to detect the severity of tremors according to the amount of generated current. We are now planning to stimulate the brains of large animals including porcine, canine, and bovine by using harvesting energy from flexible PIMNT thin film harvesters. In addition, our flexible energy harvester could be implanted inside restricted space of living body, and generate electric energy from cyclic slight movements of organs such as heart, lungs, and diaphragm to supply electricity into self-powered DBS devices in the thorax.

Experimental method

Fabrication of the flexible PIMNT thin film energy harvester

A high quality piezoelectric single crystalline PIMNT ingot with a MPB composition for this research was grown using a modified Bridgman method at iBULE photonics Co. The PIMNT ingot was cut in a thick plate shape with crystallographic orientation of [001] in the thickness direction and Cr/Au was deposited on one facial surface for the bottom electrode of the harvester. The PIMNT thick plate was bonded on a silicon wafer by using harvesting energy from flexible PIMNT thin film harvesters. In addition, our flexible energy harvester could be fabricated as follows: 1) The PIMNT thick plate was thinned to ∼10 μm thickness by grinding and chemical mechanical polishing (CMP), and subsequently the top electrode (Cr/Au) for the harvester was coated by a deposition system for a poling process. Before the Ni exfoliation process, the sample was rinsed in diluted sulphuric acid solution to clean the surface.
A tensile-stressed nickel layer (20 μm in thickness) was formed on the MIM structure by electroplating (applied current density of 100 mA cm⁻² for the sample) from a nickel sulphate solution (operating temperature of 50 °C) to spontaneously exfoliate the target PIMNT MIM. The clear delamination occurred between the piezoelectric MIM layer and the adhesive epoxy. The freestanding PIMNT film (area of 1.7 cm × 1.7 cm) was attached on a PET substrate (125 μm in thickness) by a UV sensitive polyurethane (PU) adhesive (Norland products), and then the nickel layer was eliminated in a nickel etchant (Transene). For the final PIMNT energy harvester, copper wires were fixed on the top and bottom electrodes by a silver paste. Our current process for piezoelectric PIMNT crystal growth is limited by the maximum area of 4 × 4 cm; however, we believe that the maximum device size could be increased by adopting state-of-the-art semiconductor technologies.

**Measurement of output performance**

A custom-designed linear stage and a Keithley 2612A were utilized to measure the generated electricity from the flexible PIMNT energy harvester by periodic bending motions.

**Brain stimulation in a mouse**

All animal care and experiments were performed according to the directives of the Animal Care and Use Committee of the Korea Advanced Institute of Science and Technology (KAIST, Korea). Mice were anesthetized using a cocktail of Ketamine (100 mg kg⁻¹) and Xylazine (10 mg kg⁻¹) via intraperitoneal (i.p.) injection, and then head fixed in a stereotaxic apparatus (David Kopf Instruments, Germany). Cranial coordinates of the stimulation electrode (bipolar semi-micro electrode, SNEX-100X, Rhoades medical instruments, USA) were respectively 0.0 mm and 1.5 mm posterior and lateral from the bregma. The tip of the electrode was localized at a depth of 1.1 mm from the surface of the brain. The paws of the mouse were marked with red and blue ink to track their movement. Experimental sessions were recorded using a digital camcorder (Sony Corporation, Japan) at 60 frames per second. To quantify the strength of the induced paw movements, we tracked the movements of the paws with ImageJ software (MTrack2 plugin).

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**Notes and references**


