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Recent advances and future prospects in energy harvesting technologies

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Energy harvesting technology is attracting attention as "enabling technology" that expands the use and opportunities of IoT utilization, enriches lives and enhances social resilience. This technology harvests energy that dissipates around us, in the form of electromagnetic waves, heat, vibration, etc. and converts it into easy-to-use electric energy. This paper describes the features of these technologies, recent topics and major challenges, and boldly predicts the future prospects of the development. © 2020 The Author(s). Published on behalf of The Japan Society of Applied Physics by IOP Publishing Ltd

1. Introduction

In the environment around us, we can "harvest" tiny amounts of dissipating energy and use it as available electric energy. This technology is known as energy harvesting. It is also attracting attention as a technology for achieving Goal 7 ("Ensure access to affordable, reliable, sustainable and modern energy for all") of the Sustainable Development Goals (SDGs) and strengthening the resilience of our society.[1–3] With the increasing sophistication of our society using IoT technology, we will inevitably enter the Trillion Sensor Universe, where networks consisting of one trillion sensors per year are envisioned. An initial prediction indicates that such an era will arrive within a few years.[4] In practice, it is difficult to connect each sensor to a power source individually, and therefore batteries have been continuously used for convenience despite their disadvantage in terms of power cost. However, it is actually impossible to keep replacing the batteries connected to sensors many times on the scale of the Trillion Sensor Universe. Thus, the social implementation of energy harvesting technology is becoming indispensable for sensing the environment or our own bodies.

To the best of our knowledge, the term "harvesting" has been used for photovoltaics in the visible light range since around the late 1980s.[5] In the 2000s, various energy harvesting technologies were reported.[6,7] Although the term "scavenging" was also used initially, it has recently fallen out of use, probably because its meaning is inappropriate. Figure 1 shows the overall scheme of energy harvesting technology for targets in the environment, such as electromagnetic waves, heat and vibrations. Here, I have classified energy harvesting technologies into four processes: (1) harvesting tiny amounts of energy in the environment, (2) converting the harvested energy into electric energy, (3) processing the energy in power conversion circuits and (4) utilizing the power for sensing, information processing and communication. In this article, I refer to all of these processes as energy harvesting technology. In the design of actual devices, each process should be designed in the direction opposite to the arrows in the figure. Among the energy harvesting technologies, solar cells are a well-known technology for yielding high output and have already been put into practice. However, energy harvesters are required to yield stable output from not only sunlight, but indoor light, and have been studied and developed by many researchers.[8–10] In general, the illuminance of indoor light is low and its spectrum is centered on the visible light range. Moreover, there are many types of solar cells, such as organic thin-film solar cells,[11,12] dye-sensitized solar cells[13] and perovskite solar cells.[14–16] The standardization of the method of evaluating the energy harvesting characteristics of each type of solar cell is essential for the promotion of research and development and the social implementation of the technologies.[17]

Energy harvesting technology using solar cells has been reported in many scientific papers and explained in excellent review articles by various researchers. In this article, I focus on three technologies for vibrational, radio waves and thermoelectric energy harvesting. The specifications commonly required for energy harvesters that will be applied to IoT devices are small in size with a high output. In addition, environmental durability and operational reliability are required depending on their usage environment, implementation form and cost. Here, I will point out the academic and technical issues specific to each type of technology and introduce some recent topics. As shown in Fig. 1, I assume that energy harvesting technology will be applied to the IoT field, for example, the processing and communication of sensor information, and exclude large environmental energy harvesters as well as geothermal, wave and wind power generation. Energy harvesting technologies for these energy sources and the harvesting of renewable energy were comprehensively reviewed in previous review articles,[18,19] which are recommended to the reader.

2. Vibrational energy harvesting

2.1. Features of vibrational energy harvesting

There are three methods of obtaining electric power from vibration as a kinetic energy source: electromagnetic, electrostatic and piezoelectric methods.[20] The electromagnetic method uses electromagnetic induction and inverse magnetostrictive effects. In the inverse magnetostrictive method, the magnetization state of a magnetostrictive material is controlled by applying a bias magnetic field using permanent

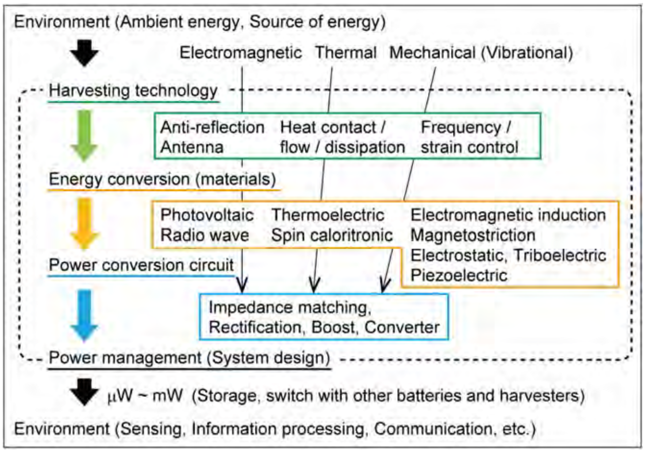

Fig. 1. (Color online) Survey of energy harvesting technologies. Technologies discussed in this paper are shown within the dashed line.

magnets and then a strain is applied to the material to generate a change in magnetic flux, which is converted into electric power using a coil.[21] The electrostatic method includes electret-type vibrational energy harvesting using MEMS and triboelectric energy harvesting.[22] A charged electrode of a capacitor is vibrated to change the electrostatic capacitance and generate power. The piezoelectric effect refers to dielectric polarization, namely, surface charges appear, when a mechanical stress or strain is applied to a dielectric. Piezoelectric energy harvesters collect the electric energy generated when vibration is applied to these piezoelectric materials.[23] For these vibrational energy harvesters, design from the viewpoint of the type of vibration to be used for energy harvesting is important in addition to the specifications commonly required for energy harvesters.[24] In general, the frequency of vibrations in the environment is 200 Hz or lower. In the case of using vibration from infrastructure such as bridges and the human body, the frequency is only about 2–3 Hz. The acceleration of such vibration rarely reaches $10\,\mathrm{m\,s^{-2}}$. The frequency and acceleration change at random in an actual environment. As is clear from the above-mentioned principles, the electromagnetic, electrostatic and piezoelectric methods have characteristic features in their output power, impedance and frequency response, and their research and development is carried out to use these features. For vibration in an actual environment, design to maximize the converted power by avoiding resonant conditions may be possible. Therefore, the features in the design of vibrational energy harvesters are impedance matching and maximization of energy conversion. For example, researchers are developing a vibrational energy harvester that efficiently harvests power from faint environmental vibrations with an acceleration of $\sim$0.1 g ($1\,\mathrm{g} = 9.8\,\mathrm{m\,s^{-2}}$) and a frequency of 100 Hz or lower using MEMS technology. This device generates current through electrostatic induction when electrets on one of a pair of opposing comb electrodes with a gap of a few micrometers are charged and the electrodes are vibrated (Fig. 2). Advanced MEMS technology is required because the effective area increases due to the structure of comb electrodes. In another study, a voltage-boost rectifier was fabricated using CMOS integrated circuits and achieved a DC output of 3.3 V. The low threshold of the rectifier circuit enabled a roughly

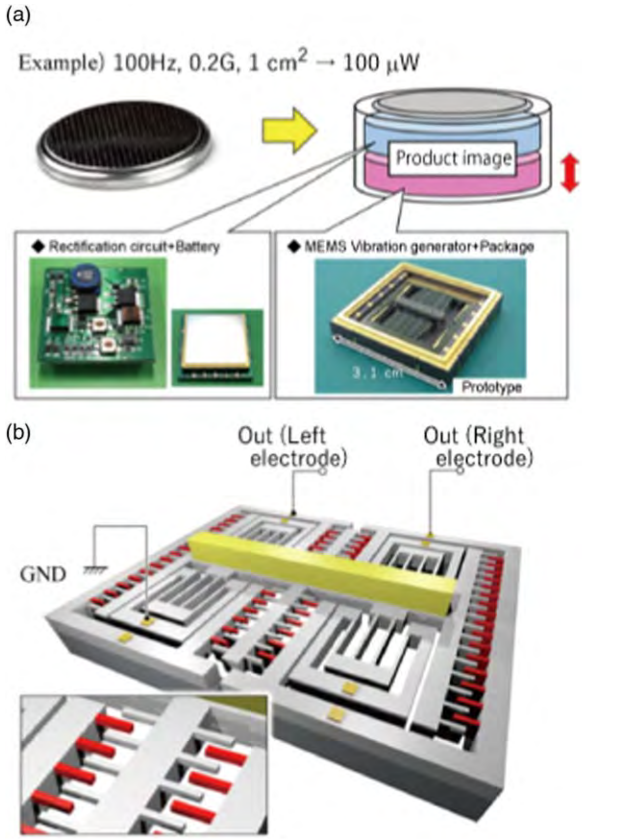

Fig. 2. (Color online) (a) Conceptual diagram of button battery type MEMS vibrational energy harvester. (b) MEMS vibrational energy harvester consisting of movable electrodes covered with electret. Electret is a material that has a permanent electrical charge.

tenfold expansion of the frequency band for the energy harvesting of MEMS vibrational energy harvesters compared with the cases using p-n diode rectifier circuits.[25)]

2.2. Topics on research and development of materials and processes

For vibrational energy harvesting by electromagnetic and piezoelectric methods, research and development of the energy conversion materials shown in Fig. 1 has been intensively carried out. The typical magnetostrictive materials used in vibrational energy harvesting by the electromagnetic method based on inverse magnetostriction are the rare-earth–iron alloy Terfenol-D and the Fe–Ga alloy Galfenol.[26] On the other hand, materials with a higher cost competitiveness than those used in other vibrational energy harvesting methods have also been developed using elements with high abundance in the Earth's crust. For example, a vibrational energy harvester using FeCo alloys was reported.[27] As piezoelectric materials, perovskite-type composite oxides such as $Pb(Zr,Ti)O_3$ (PZT) are known to have excellent energy conversion characteristics. Various film deposition methods for composite oxides have been developed to increase their area and decrease the cost.[28] To further improve the performance of PZT, attempts to realize multilayered structures[29] and nanostructures[30,31] have been reported. More concretely, it was experimentally demonstrated that the polarization characteristics of PZT can be greatly changed by coating PZT nanorods with a metal. This suggests that the performance of ferroelectrics can be improved by downsizing materials to the nanometer order and controlling the charge shielding effect rather than by employing conventional approaches such as controlling the material composition and strain.[32] However, the use of lead is restricted by the Restriction of Hazardous Substances (RoHS) Directive because of its toxicity to the human body and the environment.[33] Research and development of lead-free piezoelectric materials has also been ongoing.[34–36] Moreover, piezoelectric vibrational energy harvesters with a flexible 3D structure fabricated by a microfabrication process are expected to cover low frequencies and achieve a large strain, and are attracting attention for use in wearable devices.[37,38] Ionic liquids,[39] fluorine-containing polymers,[40,41] parylene C[42] and hydroxyapatite[43] have been intensively developed as materials for use in electrostatic electret-type energy harvesters.

2.3. Major challenges and international standardization

As mentioned above, energy harvesters are required to have high environmental durability and operational reliability. However, in the case of piezoelectric energy harvesters, for example, the material properties may change during the manufacturing process, even if the piezoelectric effect is caused by intrinsic physical properties such as the crystal structure of the material. When a strain is repeatedly applied to a material, macroscopic cracks or grain boundary segregation may occur, resulting in a reduction in the amount of power generated.[44] Clarifying the mechanism behind the deterioration of materials that occurs during the conversion of kinetic energy into electric energy and taking countermeasures are challenges for vibrational energy harvesting technology.

The evaluation of material properties with high reproducibility is indispensable towards the practical application and commercialization of any devices including energy harvesters. As mentioned above, there are various combinations of methods and energy conversion materials for vibrational energy harvesters. Hence, we need to select the combination that provides the intended properties for applications, and common standards should be prepared. International standardization for vibrational energy harvesters is being carried out by Technical Committee (TC) 47 of the International Electrotechnical Commission (IEC).[45,46] Standardization not only provides the industry with a sound competitive environment, but promotes the dissemination of achievements in research and development. In particular, when new test methods for material properties are developed, their techniques should be actively standardized to propagate the use of vibrational energy harvesting technology.

3. Radio wave energy harvesting [Radio frequency (RF) energy harvesting] [47–49]

Radio waves are a type of electromagnetic wave and are defined as electromagnetic waves with a frequency of ⩽3 million MHz (3 THz) in the Radio Law. IEC similarly defines a radio wave as "an electromagnetic wave propagated in space without artificial guide and having by convention a frequency lower than 3000 GHz". It is clear from the fact that we can search using our smartphones at any time, even on an airplane or a train, that radio waves can be harvested everywhere. In most cases, the harvested radio waves are electromagnetic waves originally generated electrically, and those in a certain frequency band are selectively transmitted for specific purposes. Therefore, radio wave energy harvesting includes rectification. Moreover, wireless power supply systems that are commercially available for various applications transmit radio waves with energy, which is similar to radio wave energy harvesting. Radio wave energy harvesters should efficiently perform the processing explained in Fig. 1 with a compact antenna because they need to be small, similar to other energy harvesters, and the electric energy of the radio waves to be harvested is extremely small. Although the vibrational energy harvesters introduced in the previous section require a similar circuit design, radio wave energy harvesters require the solution of other problems because of the high frequency of radio waves. For example, to design a boosting circuit for energy storage, the problem of reduced efficiency of power conversion, or power loss, in circuits must be solved. Towards the 5 G era, energy harvesting from high-frequency bands is advantageous for reducing the size of antennas, but the circuit design must be optimized to satisfy the conflicting demands for each application.

Rectennas are antennas integrated with rectifier circuits and can convert harvested radio waves into DC power. A wide range of research and development of rectennas for radio wave energy harvesting has been conducted from device technology to rectenna evaluation.[50–52] For example, a high-sensitivity backward diode consisting of III–V semiconductor nanowires was developed as a rectifier that replaces the preceding GaAs Schottky barrier diodes and is expected to efficiently convert even sub-μW-class weak radio wave energies into electric power (Fig. 3).[53,54] In addition, the rectification characteristics of diodes consisting of silicon-on-insulator (SOI) FETs with steep current characteristics, called p-n junction body-tie SOI-FETs, have been markedly improved, and they are expected to be applied to radio wave energy harvesting.[55–57] Moreover, flexible diodes made of molybdenum(IV) sulfide (MoS_2), a 2D semiconductor, were developed and proved to be promising for rectennas in the 2.4 GHz frequency band.[58] There is still much room for new materials and structures to bring about breakthroughs in

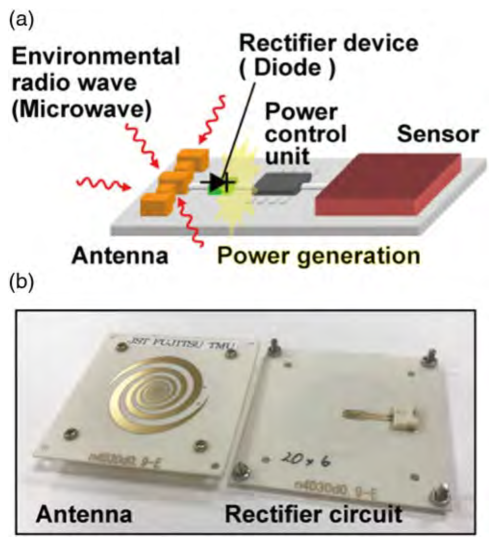

Fig. 3. (Color online) (a) Conceptual diagram of microwave power harvesting. (b) Newly developed antenna and rectifier consisting of a backward diode.

terms of not only the development of diodes, but the advancement of small high-efficiency antennas. Future research and development is expected to lead to major breakthroughs in radio wave energy harvesting.

4. Thermoelectric energy harvesting

4.1. Features of thermoelectric energy harvesting

Various surveys have shown that we waste at least 70% of our primary energy, which dissipates as waste heat.[59] A survey reported that the temperature of the dissipating heat is mostly below 100 °C. The minute energy of such heat can be harvested and converted into electric energy by thermoelectric energy harvesting, which is attracting attention as a technology for providing an independent power supply for various IoT devices.[60,61] When a temperature difference ΔT is given to the two ends of a conductor, a voltage ΔV proportional to ΔT is generated. This effect is called the Seebeck effect, and the proportionality coefficient S ($=\Delta V/\Delta T$) is called the Seebeck coefficient. Thermoelectric materials are frequently evaluated by the dimensionless figure of merit $ZT = (S^2\sigma/\kappa)T$, where σ is the electrical conductivity and κ is the thermal conductivity. Here, $S^2\sigma$ in the numerator is called the power factor (PF) and indicates how much power W can be obtained with a temperature difference of 1 °C per unit length.[62] The thermoelectric conversion efficiency increases with ZT, and it is required to exceed 1 for practical purposes. As shown in Fig. 1, the properties of energy conversion materials should in general be metallic in order to decrease the contact resistance of the electrodes, and furthermore in the case of thermoelectrics to be favorable for ZT and lower the resistance of power generation from harvested heat. However, ordinary metals cannot achieve a high thermoelectric conversion efficiency in general because the number of free electrons does not greatly change with the temperature and the Wiedemann–Franz law, stating that σ is proportional to κ, holds. Moreover, S, σ and κ in the equation for ZT are functions of carrier concentration and are difficult to control independently. Thus, various breakthroughs are needed to improve the thermoelectric properties of materials.

4.2. Topics on development of materials[63]

As a means of solving a bottleneck that prevents the increase in ZT, the selective enhancement of phonon scattering by microstructures has been attempted.[64–67] This involves reducing only κ_{ph} on the basis of the assumption that the thermal conductivity κ is the sum of the contributions of electrons and phonons to κ, that is, κ_e and κ_{ph}, respectively. This attempt is also known as a material design guideline called “phonon glass electron crystal”.[68,69] In addition, researchers have attempted to improve the effective thermoelectric properties of materials by controlling their specific crystal structures[70,71] and utilizing microfabrication technology, which means the use of nanostructures in a broad sense.[72,73] Moreover, the introduction of magnetic ions is one of the most promising methods.[74,75] For example, the increase in the effective mass of carriers has been attempted through the formation of polarons by spin–orbit interaction. The use of 2D materials[76–80] and band engineering[81,82] have also been studied intensively with the aim of enhancing the PF. Recently, significant progress has been made in improving ZT by band engineering. A report showed that the ZT determined from the thermal properties of thin-film Heusler alloys based on $Fe_2V_{0.8}W_{0.2}Al$, which was measured by multiple laboratories while confirming reproducibility, has reached 5 in the range of 350–400 K.[83] This was observed in a thin-film material with a metastable crystal structure in its bulk state. It is highly expected that completely new thermoelectric materials can be developed by controlling the crystal phase in thermal non-equilibrium conditions.[84]

Flexible organic materials are attracting attention as thermoelectric materials for wearable applications.[85–87] Even if the thermoelectric figure of merit of organic materials is inferior to that of inorganic materials, organic materials can be practically used by increasing their area to obtain the power needed. Carbon nanotube thin films have been studied and developed as thermoelectric materials because stable n-type doping can be achieved. High PFs of carbon nanotube thin films at RT have been reported.[88–90] Silicon and its compounds are drawing attention as thermoelectric materials developed from human- and environmentally friendly elements.[91–93] A p-type SiGe layer deposited on a flexible substrate in a low-temperature process has achieved a high PF of 280 $\mu W\,m^{-1}\,K^{-2}$.[94] Conductive oxides have not been focused on as thermoelectric materials because of their low carrier mobility and high thermal conductivity. In 1997, however, excellent thermoelectric properties were discovered in the layered cobalt oxide Na_2CoO_4[95] and then in $(Ca_2CoO_3)_xCoO_2$,[96] $SrTiO_3$, and so forth.[97,98] As a result, conductive oxides have attracted much attention as materials for energy harvesters, which are required to have low environmental impact and high environmental durability. Not only the crystal structure, but the electron and phonon properties of oxides can be easily controlled by element substitution. Recent trends of research on conductive oxides include (1) the improvement of the Seebeck coefficient by the control of orbital degeneracy, (2) the suppression of the phonon contribution to thermal conductivity using the fluctuation of the orbital degree of freedom and (3) the suppression of thermal conductivity with the use of interfaces (Fig. 4).[99,100]

There have been various advances in techniques for generating, detecting and controlling spin current in the field of spintronics. A new research field that emerged from this field is spin caloritronics, which studies the control of spin current with heat. This was triggered by the discovery of the spin Seebeck effect in 2008, in which spin current is generated by a temperature difference.[101] Subsequently, an electromotive force (spin voltage) was observed in a magnetic insulator, contributing to significant academic progress.[102] Moreover, research on spin caloritronics has been carried out for the development of flexible applications and the further improvement of their performance.[103–108] In the Seebeck effect, an electromotive force is generated in the same direction as the temperature difference. In contrast, the temperature difference, magnetization and the electromotive force (Nernst voltage) are all perpendicular to each other in the Nernst effect. When the Nernst effect is used, it should be possible to obtain effectively large power by forming a module itself into a sheet. The Nernst effect in magnetic materials is called the anomalous Nernst effect, which has been observed in various materials.[109–112] For example, the giant anomalous Nernst effect observed in Co_2MnGa is related to the topology of the electronic structure called the Weyl point and has been explained as a quantum critical phenomenon.[113] Graphene, a 2D material, is well

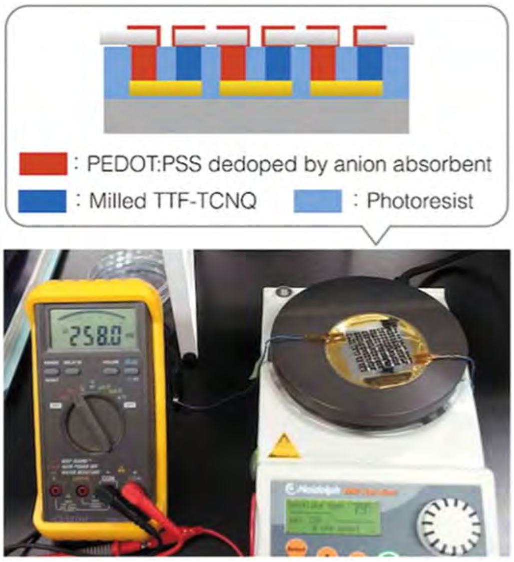

Fig. 4. (Color online) Schematic of p-type module for organic thermoelectric energy harvesting. PEDOT:PSS and TTF-TCNQ are used as the p-type and n-type thermoelectric materials, respectively, and these are alternately connected in series to form the p-type module. Voltage exceeding 250 mV is generated by providing a temperature difference between the upper and lower surfaces. N. Satoh, M. Otsuka, T. Ohki, A. Ohi, Y. Sakurai, Y. Yamashita and T. Mori: "Organic p-type thermoelectric module supported by photolithographic mold: a working hypothesis of sticky thermoelectric materials", Science and Technology of Advanced Materials, 19:1, 517-525, (2018), DOI: 10.1080/14686996.2018.1487239 Ref. 100.

known as a typical material that has a Dirac cone in the energy-band structure and exhibits topological properties. Considering the fact that two-dimensionalization contributes to improving the thermoelectric properties of ordinary thermoelectric materials, topology is expected to play a major role in the design of spin caloritronics materials. In practice, an anomalous Nernst effect due to the topology of the electronic structure was observed in the antiferromagnetic manganese alloy Mn_3Sn, enabling the harvesting of energy using spin current at RT in zero magnetic field.[114)]

4.3. Major challenges and thermophysical metrology

Although various thermoelectric materials have been reported, a considerable number of them show a sharp decrease in the figure of merit near RT. This is why Bi_2Te_3 with good thermoelectric properties near RT is almost the only choice of material for the practical IoT applications targeted in this article. Furthermore, it becomes difficult to stably obtain a sufficiently large temperature difference near RT. Hence, the improvement of the harvesting technology explained in Fig. 1 is required. However, the degradation of thermoelectric materials and electrode interfaces is alleviated at low temperatures, which is advantageous from the viewpoint of reliability. Thermoelectric materials are assumed to be used at relatively high temperatures and their degradation mechanism has been investigated from the viewpoint of ionic conductivity.[115,116)] The clarification of the degradation mechanism of thermoelectric materials assuming their use for IoT applications will be future work. In the search for new materials that will be important in the future, some cases of using materials informatics for the search have been reported. Indeed, structures that can reduce thermal conductivity, and new material systems have been discovered by machine learning, indicating that materials informatics will be a powerful tool for searching for materials.[117–120)] Research activities to obtain directions for material development from various data on thermoelectric properties will become increasingly popular.[121)] Completely new research fields have emerged in phonon engineering.[122–124)] Researchers have realized the control of thermal conduction in phononic crystals with a periodic nanostructure as well as thermal collection using a lens structure with a radial array of holes.[125–128)] A technique for selectively generating heat at the nanometer scale using plasmons has also been developed.[129)] Techniques related to the control of the heat current will have a large ripple effect and are expected to achieve further advances in the future.

When the heat current of thin-film thermoelectric materials is controlled using miniaturized structures, an accurate measurement of the thermophysical properties in the miniaturized structures is a major difficulty. For example, in a previous study, the temperature of a sample was measured with a nanometer spatial resolution by electron energy-loss spectroscopy in a transmission electron microscope on the basis of the dependence of the plasmon peak shift on the temperature of the sample.[130)] However, the accurate measurement is impossible unless the plasmon peaks are sufficiently sharp. To solve this problem, microscopy techniques have been applied[131)] and methods based on scanning probe microscopy have been developed.[132)] A technique for calculating the temperature change and thermal effusivity at the tip of a probe and simultaneously mapping the Seebeck coefficient and thermal conductivity from spatial information on the potential difference has also been reported and is expected to be indispensable for evaluating the reliability of thermoelectric energy harvesters.[133,134)] A thermoreflectance method has become a popular means of evaluating the thermal diffusivity and thermal conductivity of thin films.[135,136)] One side of a thin film is instantaneously heated by pulsed light to detect the temperature response at a position a certain distance from the film. This temperature response is measured as the temperature dependence of the reflected intensity of the probe light, and its time dependence is analyzed to determine the thermal diffusivity and thermal permeability. The analysis of the experimental data obtained from reference samples enables the calculation of the thermal resistance induced at the interface between the position of the incident light and the measurement position of the reflected intensity. Furthermore, the interface of a thin film on the side of the substrate can be directly heated when long-wavelength light that penetrates through the substrate is used. Therefore, the thermal properties of the thin film in the thickness direction can be clarified by applying the thermoreflectance method to the surface of the thin film.[83)] To increase the use of thermoelectric energy harvesting technology in society, it is necessary to establish techniques for evaluating the properties of materials with a sufficiently high accuracy as well as evaluation protocols to ensure their reproducibility. For example, the measurement of the Seebeck coefficient requires the measurement of the electromotive force, but the internal resistance of voltmeters is not infinite. Moreover, a measurement sample is always connected to an electrode, and the reference value of the electrode must be considered, that is, the Seebeck coefficient cannot be defined with the values of the sample alone. Namely, the absolute value of the Seebeck

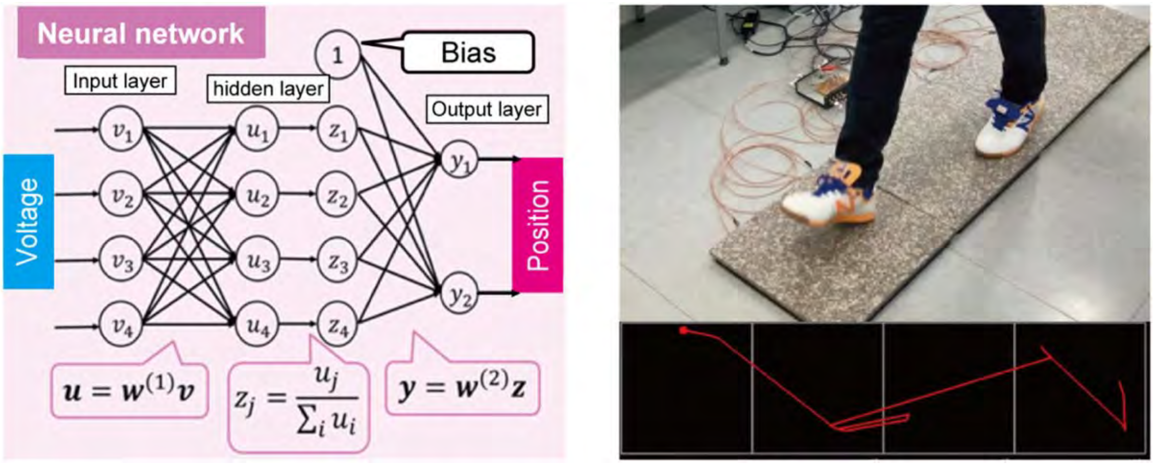

Fig. 5. (Color online) Example of a piezoelectric vibrational energy harvester. We have succeeded in realizing a gait position sensor by utilizing machine learning. In addition, by using it with vibration power generation, the wireless and infrastructure-built-in-type sensor system becomes possible. It is expected that the utilization of transportation infrastructure can be analyzed from the gait signal.

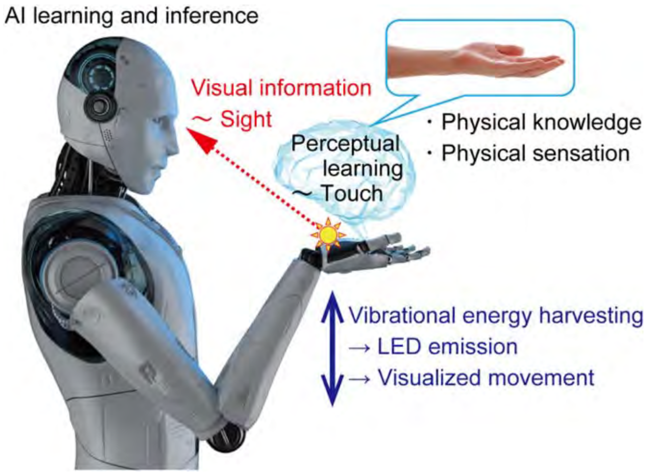

Fig. 6. (Color online) Possible future of energy harvesting technology. AI implemented in a robot with a motor function perceptually learns the movement of the arm as visual information by using the vibrational energy harvester and LED installed on the robot. AI acquires the physical knowledge and sensation.

coefficient includes uncertainty if the electromotive force is measured just as it is.[137–139] The result of a round-robin test showed that the uncertainty of the figure of merit ZT was as large as ∼20%.[140] Recently, a research group has superimposed AC on DC and developed a measurement method to obtain the Seebeck coefficient from the Thomson coefficient, which is determined from a sample alone.[141] In the future, the development of reference samples that exhibit stable properties in a desired temperature range is expected,[142] and the establishment of international standards for the evaluation protocols for materials and modules is desired.

5. Conclusion

Focusing on vibrational, radio wave and thermoelectric energy harvesting, I described their technical features, recent topics and future challenges. In particular, for vibrational and thermoelectric energy harvesters, it is necessary to develop environmentally friendly and highly reliable materials, and standardize the techniques for evaluating their properties. I hope that early adopters will appear in unexpected fields in the near future if sufficiently mature energy harvesting technology stimulates academic research and development activities, and provides commercial value to meet user demands. As the trend of low power consumption further continues in IoT-related technology, energy management techniques and evaluation kits will be developed for the connection of energy harvesters to this technology.[143,144] Energy harvesting technology is expected to play a leading role as a technical enabler in the advancement of smart cities and societies, and in various fields such as advanced medicine.[145,146]

As a final remark, I will predict the future of energy harvesting technology. As shown in Fig. 1, the energy harvested from electromagnetic waves, heat and vibrations is used for sensing the environment and processing the information for communication. Such ambient energy is "information" itself of the environment. Therefore, energy harvesters' signals can be analyzed to find latent regularities in the environment by machine learning, and these regularities can be used as data for predicting the future of the environment.[147] Figure 5 shows a gait position sensor that uses machine learning for the analysis of signals obtained from a vibrational energy harvester. This sensor is expected to be used as a technology for predicting the usage status of transportation infrastructure by the analysis of the obtained data. Vibrational energy harvesters can convert the movement of the human body into electric energy and enable visualization of such a movement using light-emitting diodes. In practice, this technology has promoted the integration of art and science through entertainment.[148] As an extension of such technical development, there may be a future where artificial intelligence (AI) acquires physical knowledge and sensation by perceptually learning tactile information, as shown in Fig. 6.[149,150] The AI implemented in a robot can obtain visual information as an image that contains kinetic information converted into light intensity. In addition, the AI learns as visual information of the motion commanded by the AI itself does not necessarily produce the result intended by control signals because vibrational energy harvesters are independent power supplies. I have described the future prospects of the applications of energy harvesting technology assuming that the visual sense plays an important role in acquiring neonatal somatic sensation. I hope that this article inspires the reader to ponder whether such applications will be possible in the future.

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