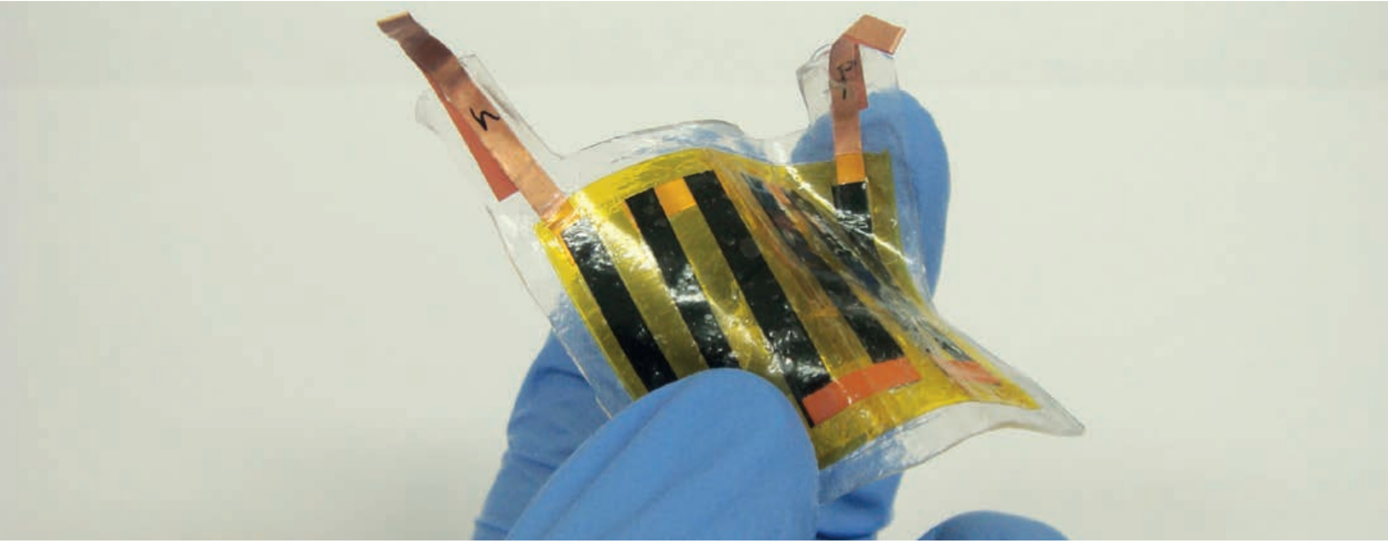

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A bendable thermoelectric device made from modified carbon nanotubes can generate electricity from a temperature gradient.

Semiconductors

Generating power from waste heat

Additives improve the thermoelectric efficiency of carbon nanotubes

Bendable devices that convert waste heat into useful electricity have become much more efficient, thanks to films made of tiny carbon nanotubes developed at NAIST in Japan[1]. These thermoelectric films generate a voltage when one side is hotter than the other and could be used in a variety of applications, including battery-free sensors and energy-saving technologies. "More than 5 per cent of the fuel consumption of gasoline-powered vehicles could be saved by thermoelectric heat recovery systems in the near future," says Tsuyoshi Kawai of the Laboratory for Photonic Molecular Science at NAIST, who led the research.

Most thermoelectric devices are solid, inflexible materials made from highly toxic elements. So Kawai and his colleagues created lightweight and flexible thermoelectric films made of hollow straws of carbon atoms mere billionths of a metre wide, called single-walled carbon nanotubes (SWNTs). These films (see figure) can closely hug the curved surfaces of an engine or pipe, maximizing the power they generate.

Unlike a metal wire, SWNTs do not carry current as a flow of electrons. Instead, the nanotubes rely on the movement of positively charged 'holes' left behind by missing electrons — they are known as p-type semiconductors. The efficiency of thermoelectric devices made solely from p-type materials is very low — unless teamed with n-type semiconductors, which have a surfeit of electrons. But researchers have previously struggled to create stable and flexible n-type thermoelectric materials.

Kawai's team studied 33 different carbon-based molecules to assess whether they could transform SWNTs into n-type semiconductors. They found 18 molecules that could. The best was triphenylphosphine (tpp), whose phosphorus atoms inject electrons into the SWNTs. The researchers filtered the tpp-SWNTs from a liquid to create air-stable n-type films, and paired them with p-type SWNTs that had been enhanced with another additive, tetracyanoquinodimethane (TCNQ). The device was sealed inside a polymer and wrapped around a pipe that was hotter at one end than the other.

The team found that a temperature difference of 20 degrees Celsius generated 110 nanowatts of power at a voltage of 6 millivolts. "We have demonstrated the first example of flexible thermoelectric sheets with this bipolar structure," says Kawai.

The team's survey of different additives also revealed which molecules are best suited to fine-tuning the behaviour of the SWNTs, which is helping to design even more efficient and stable n-type materials. "We are now cooperating with some industrial companies for future commercial applications," says Kawai.

Reference

1. Nonoguchi, Y., Ohashi, K., Kanazawa, R., Ashiba, K., Hata, K. *et al.* Systematic conversion of single walled carbon nanotubes into n-type thermoelectric materials by molecular dopants. *Scientific Reports* **3**, 3344 (2013).

More information about the group's research can be found at the Photonic Molecular Science Laboratory webpage:
http://mswebs.naist.jp/LABs/kawai/english/index.html