Spin caloritronics

Utilising and controlling heat with spin and magnetism

One of the biggest obstacles to making energy-efficient devices is dealing with heat production. Any kind of work, including the flow of electricity in a circuit, often generates waste heat as an unwanted side product, limiting the ultimate energy efficiency of the device. Dr Ken-ichi Uchida at the National Institute for Materials Science, Japan, has been exploring how controlling electrons using a process called spin caloritronics could turn waste heat into useful work.

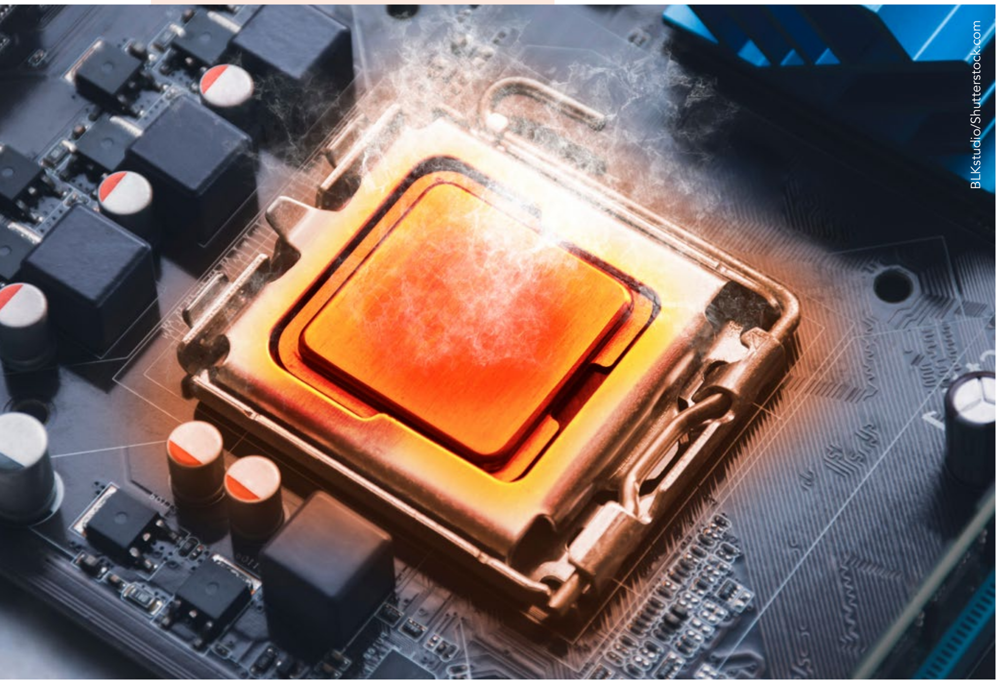
At a certain point in recent history, rapid developments in computing power seemed to be unstoppable. Every year, more and more transistors were being squeezed onto computer chips, making ever faster calculations possible. Smaller microchips giving faster performance have entirely revolutionised the role of electronic devices in our lives, with today's handheld smartphones easily able to outpace older supercomputers that could occupy whole rooms.

However, the relentless pace of technological development has started to show signs of grinding to a halt. Many of the technical limitations to make smaller and smaller chips have been overcome, with machining techniques now being capable of slicing and shaping pieces with accuracies on the same size scale as atoms.

This has meant that the endless efficiency gains and Moore's Law (which describes this performance gain in terms of components, essentially stating that the number of transistors in an integrated circuit doubles every two years) – has come unstuck. This seemingly insurmountable problem in electronics can be put down to the issue of thermal management.

An electrical current involves the movement of electrons through a circuit. Each of these little particles carries a small amount of electrical charge. Normally, a circuit starts with some kind of power source – a battery or power supply – and then there is a device that uses this electrical energy provided by the electrons to fulfil a purpose: that might be in the form of converting it to light in a lightbulb or kinetic energy to move a motor.

There is always one problem though. As the electrons move around a circuit, they encounter small impurities and other barriers to their path that causes resistance in the circuit. As they collide with these, their useful electrical energy becomes lost as heat and the overall energy efficiency of the device is reduced. Some researchers, including Dr Ken-ichi Uchida at the National Institute for Materials Science in Japan, think this process of electrical energy to heat conversion might not just be an energy efficiency problem, but an opportunity. This is where the field of spin caloritronics comes in.



HANDLING SPIN

Uchida and his group have been trying to harness electrons and their fundamental properties to play with electrical energy to heat conversion. Every electron has a quantum mechanical property called spin, which determines how they will interact with other electrons of the same or opposite spin, as well as with external magnetic fields.

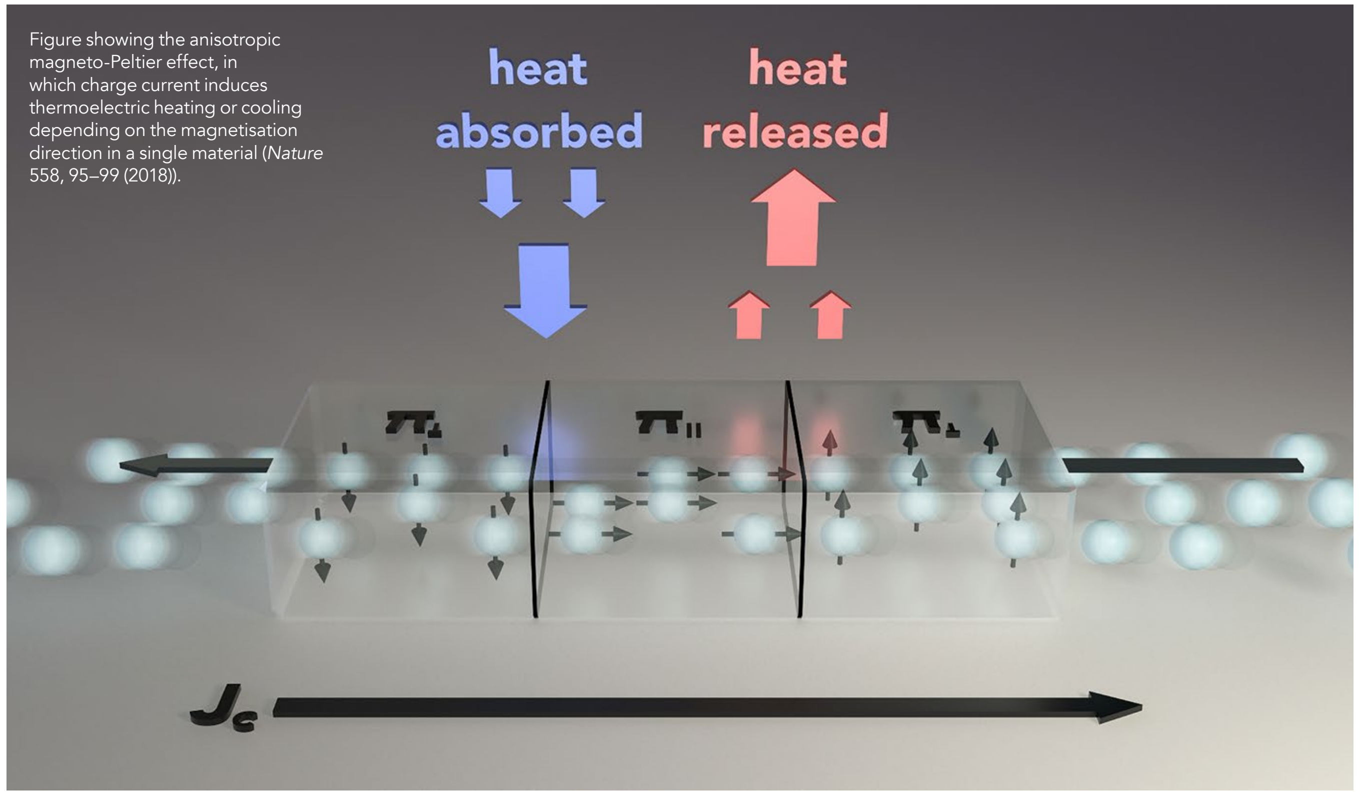
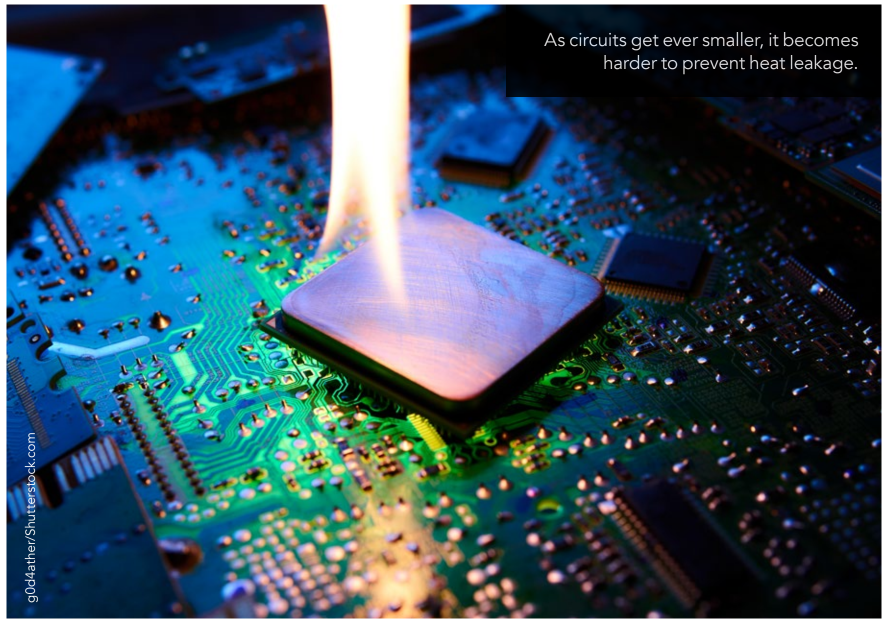


Figure showing the anisotropic magneto-Peltier effect, in which charge current induces thermoelectric heating or cooling depending on the magnetisation direction in a single material (*Nature* 558, 95–99 (2018)).



As circuits get ever smaller, it becomes harder to prevent heat leakage.

What seems to be the insurmountable problem in electronics is the issue of thermal management.

An electron can either spin up or spin down. Generally, electron spin is the origin of magnetism; since spins are aligned in the same direction in magnetic materials, they have macroscopic magnetisation. Uchida has been finding out how to play with these electron spins as a way of controlling how the electrons behave and affect thermal and thermoelectric transport properties.

Electronics is all about controlling electron movement and flow, but spintronics not only involves manipulating the electric charge of electrons but also the magnetic moment associated with their spin. Spintronics can offer a solution to the problem electrical circuits are facing regarding their size limitations. As circuits get smaller and smaller, it becomes harder to deal with heat leakage between channels that disrupt performance and cause noise.

Spintronics offers a way to create far more densely packed devices on a nanoscale, and it is already being used as a means of manufacturing integrated circuits, magnetic sensors and magnetic RAM for computing. In a simplified picture, spintronic devices exploit changes in the spin of the electrons as an additional way to carry, transfer and record information, in a similar way to how charge can be used to perform logic operations in a standard electronic circuit.

SPIN CALORITRONICS

Uchida has been using many of the principles of spintronics to assess how electron spins are involved in heat–spin and heat–charge interconversion processes. A device with perfect energy efficiency would not produce any thermal waste energy; however, all electronic and spintronic devices will have some thermal losses.

Better understanding spin caloritronics may enable designers to place more transistors onto chips.

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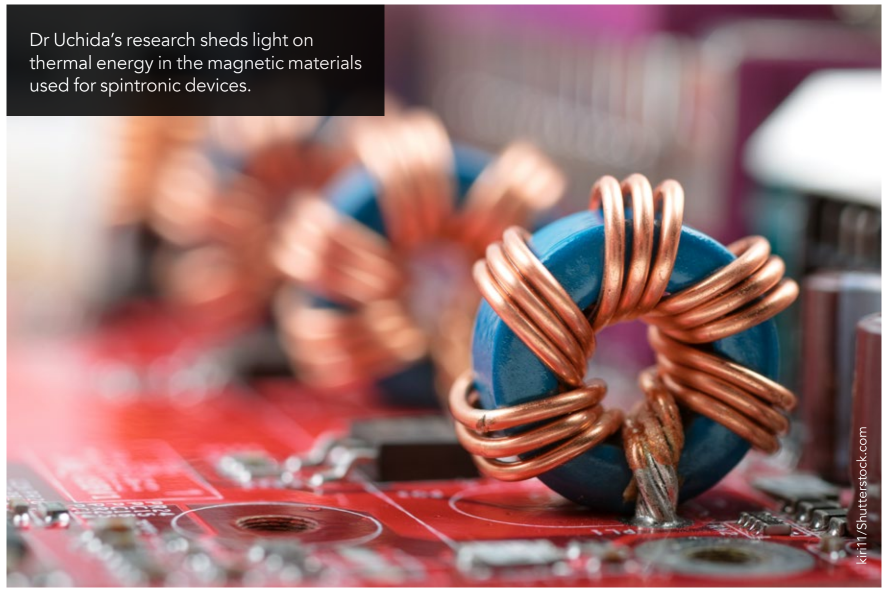
Understanding and exploiting these phenomena still forms part of a very young field of research. Uchida has been helping to develop experimental techniques and mechanisms that can be used to measure and understand these fundamental interactions between the inherent properties of the electrons and thermal energy in the types of magnetic materials used for spintronic devices.

With Uchida's understanding of these processes, a framework for thermal management in spintronic devices can be established. This would help influence how such devices were manufactured to take advantage of several spin-caloritronic effects.

Recent research has shown that transferring thermal energy is indeed spin-dependent, and it is possible to create versatile thermoelectric converters based on magnetic and spintronic materials, where heat–charge conversion properties can be controlled by changing the magnetisation direction. Such an active thermal management was impossible if only the conventional thermoelectric effect was used.



Dr Uchida's research sheds light on thermal energy in the magnetic materials used for spintronic devices.

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The new field of spin caloritronics enables active thermal management.

MATERIALS OF THE FUTURE

Finding ideal materials for such spin caloritronics applications means finding materials that have high heat–spin–charge conversion performance. Even though only a very limited number of materials have been investigated, Uchida's guidelines in his review of the work in this area show the factors that need to be considered when it comes to finding the spin-caloritronic materials of the future.

Taking a different approach to designing circuitry and no longer relying only on the charge properties of electrons may be the answer to overcoming the thermal waste problem, and being able to place more and more transistors onto chips. Building ever smaller electronic devices becomes immensely challenging, but taking advantage of different properties of the electron may pave the way for new energy-efficient materials.

Developments in this area may happen very quickly and one of the keys for further developments is the creation of new materials that exploit the large spin-caloritronic effects. Uchida emphasises that the heat control functionalities that spin caloritronics make use of are still based on the intrinsic physical properties of spintronic and magnetic materials. The advantage of this is that there are many years of research and development of experimental techniques which facilitate the design of the materials themselves. This means researchers will be able to draw on this knowledge and expertise to exploit new heat–spin–charge interconversion properties.

With new theoretical developments explaining how these phenomena work in more detail, a whole new class of materials can be developed and a new era of energy-efficient, high-performance devices can be created. The concept of 'thermal waste energy' may be a thing of the past, and instead, an opportunity will arise for thermoelectric and spin-caloritronic materials to have a new energy source.

Behind the Research

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Research Objectives

Development of novel science and technology for thermal energy engineering based on magnetic and spintronic materials.

Detail

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Bio
Since 2016, Dr Uchida has been Group Leader of the Spin Caloritronics Group, at the Research Center for Magnetic and Spintronic Materials, National Institute for Materials Science. From 2014 to 2016, he was Associate Professor, Institute for Materials Research, Tohoku University. Since 2019, he has also been professor, Institute for Materials Research, Tohoku University.

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Collaborators
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Personal Response

What do you think will be the next big development in spin caloritronics?

" First: the expansion of the physics of spin caloritronics to other fields and materials is important. One of such research directions is polarisation caloritronics using ferroelectrics. Recently, unconventional thermoelectric effects based on dielectric polarisation transport has been predicted theoretically but has not been demonstrated experimentally yet (*PRL* 126, 187603 (2021)). Its experimental verification requires the interdisciplinary fusion of spin caloritronics, ferroelectrics, and nanoscale science.

Second: to realise the application of spin caloritronics, it is necessary to significantly improve the thermo-spin/thermoelectric conversion performance. Thus, it is essential to develop materials with high spin–charge–heat interconversion properties. "

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