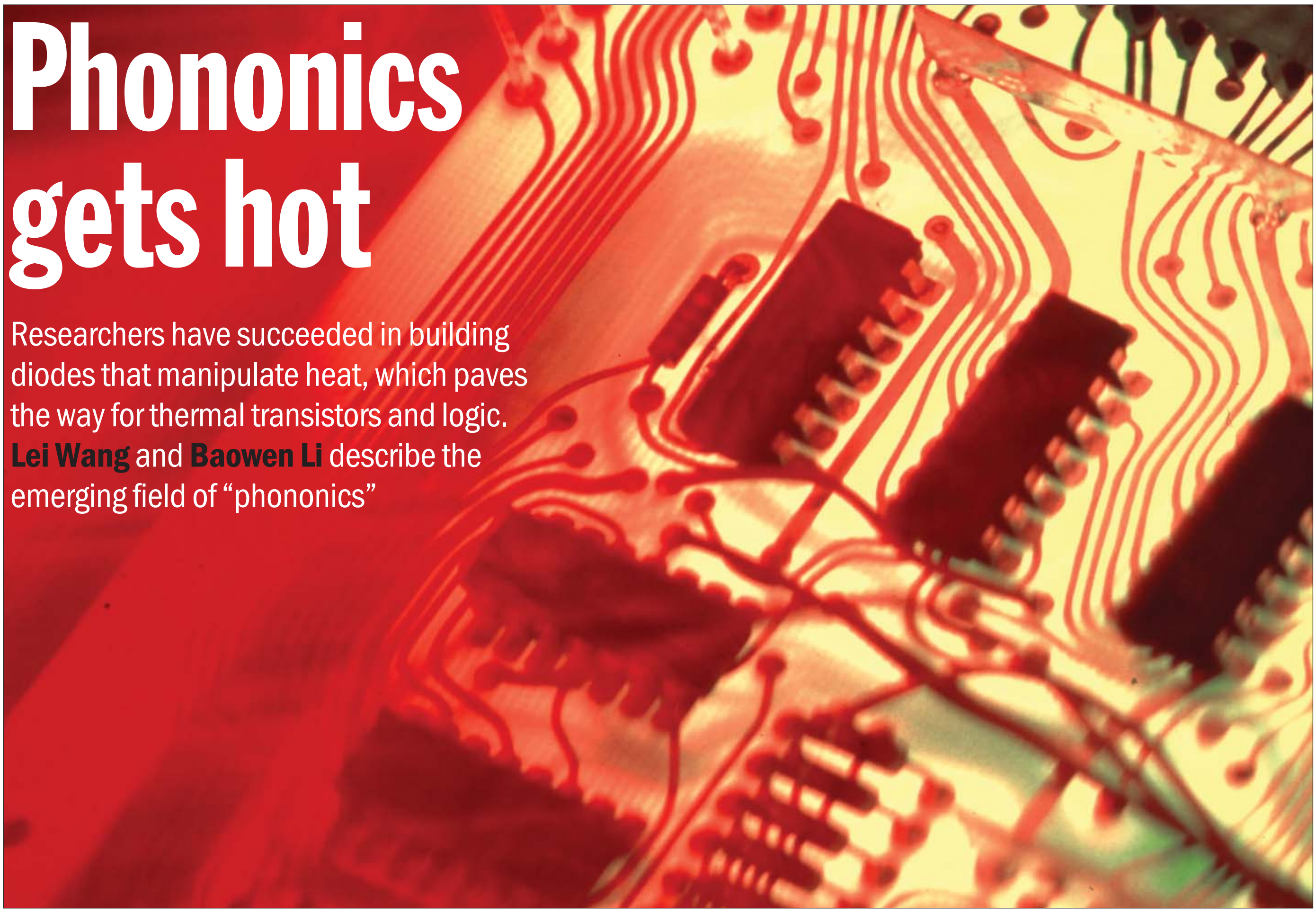
Phononics gets hot

Researchers have succeeded in building diodes that manipulate heat, which paves the way for thermal transistors and logic. **Lei Wang** and **Baowen Li** describe the emerging field of "phononics"



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When it comes to transporting energy, nature has two vital tools at its disposal: conduction by heat and by electricity. But these two phenomena have never been treated equally by scientists. Electricity, via the transistor and other electronic devices, has enabled technological developments that have transformed many aspects of our lives. But similar devices that allow the flow of heat to be controlled are still not available, despite many decades of research.

The problem is that it is much harder to control the flow of heat in a solid than it is to control the flow of electrons. Unlike electrons, the carriers of heat (phonons) are not point particles with definite properties but bundles of energy that have no mass or charge and are therefore unaffected by electromagnetic fields. However, nature has been managing the flow of heat for billions of years, especially inside living bodies – you only need consider how the body manages to keep each internal organ at just the right temperature to see why. It must therefore be possible, even if it requires a totally different physical mechanism, to control heat technologically.

We may, however, be about to turn "phononics" from a dream into reality. Specifically, researchers have recently built thermal diodes, thermal transistors and thermal logic gates, which are the basic components of functional thermal devices. Such components also raise the possibility that heat – long regarded as useless or harmful in electronic circuits – could be used to process information. Phononics would therefore add a new physical dimension to information processing in addition to electronics and photonics.

One-way heat flow

The most fundamental phononic component is the thermal diode – a device that can conduct heat in only one direction. The directional thermal effect was first observed in a copper–cuprous-oxide interface by the physicist Chauncey Starr at Rensselaer Polytechnic Institute in New York in the 1930s. Over the next three decades, researchers made extensive studies of heat flow across such material interfaces, often involving steel and aluminium. But without a rigorous theoretical foundation such as nonlinear dynamics, or sufficient computing power to simulate the process, these early heat diodes remained nothing more than interesting toys.

That situation has changed dramatically over the last few years. In 2002 Marcello Terraneo at the Universitá degli Studi dell'Insubria in Como, Italy, and co-workers proposed a simple model of a thermal diode based on resonance (*Phys. Rev. Lett.* **88** 094302). All physical systems have a natural frequency, which means that energy can be transported very efficiently by exciting the system with vibrations at that frequency. This is what makes it possible to push a child high on a swing with only minimal effort. Since thermal energy corresponds to the vibrations of atoms or molecules, the same principle applies to materials: heat is easily exchanged between two materials if their resonant frequencies match; if they do not match, then transferring heat becomes much harder.

Terraneo looked at what happens when a nonlinear material with a resonant frequency that depends strongly on temperature is sandwiched between two

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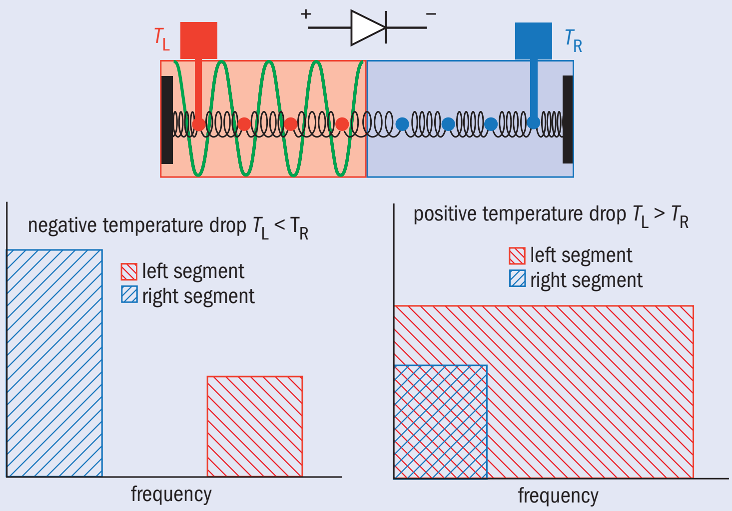
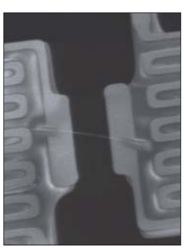
1 Thermal diodes



By coupling two materials or "segments" with different resonant frequencies together, a thermal current can be stopped at or let through the interface depending on the temperatures of the segments (top). In this model, one segment (blue) is a chain of particles each of which is connected to its nearest neighbours by elastic springs that satisfy Hooke's law, while the other (red) is an identical chain but is subject to a sinusoidal potential (green). If the temperature at the red segment is less than that at the blue (bottom left), then the resonant frequencies of the blue segment always concentrate in low frequencies, while those of the red segment concentrate at high frequencies (since the particles are confined in the valleys). As a result, the vibration frequencies of each segment do not match and heat (which is the result of vibrations of the particles) cannot flow very efficiently. However, when the temperature at the red segment is greater than that at the blue (bottom right), the particles can move freely between the barriers and thus their vibration frequencies partly extend to low frequencies, which matches those of the particles in the right segment. This match/mismatch mechanism makes directional thermal conduction, and also negative differential temperature resistance (NDTR), possible. NDTR is essential for making thermal switches and transistors.



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One-way flow
Connected to two electrodes, the thin line in the middle is a carbon nanotube at the heart of the first ever microscopic solid-state "thermal rectifier".

nearly linear segments, the frequencies of which hardly vary at all with temperature. He found that the frequencies of the materials match one other when a temperature drop (analogous to a voltage drop in an electric circuit) is introduced in one direction and mismatch one another when the temperature drop is in the other direction. The net result is that heat can easily flow in one direction through the sandwich but not the other.

In 2004 the present authors modified this model using segments made up of a chain of particles subject to a sinusoidal potential, which has a resonant frequency that depends much more sensitively on temperature than that in Terraneo's model (figure 1). We also reduced the number of segments from three to two, thus forming a single interface. Overall, this increased the rectification effect (i.e. the ratio of the heat currents in different directions) by up to three orders of magnitude (*Phys. Rev. Lett.* **93** 184301).

Inspired by this theoretical progress, in 2006 Chih-Wei Chang and co-workers at the University of California at Berkeley built the first microscopic solid-state thermal rectifier (*Science* **314** 1121). The researchers attached a heater and a sensor to the two ends of a nanotube, which allowed them to calculate its thermal conductivity. They then deposited heavy, platinum-based particles non-uniformly along half the length of the nanotube so that the temperature dependence of the resonant frequency varies along the tube. This match/mismatch of frequencies meant that the conductance was 3–7% greater in one direction than it was in the other. The rectification observed by Chang is smaller than the predicted maximum. This is mainly because the Berkeley system (which is a few microns in length) is much larger than the system that was modelled, which meant that the role of the interface was suppressed. Nevertheless, the work was a great step forward. We should remember that the first electric diode and transistor in 1940s were also much less efficient than those available today.

In fact, just a few months later Ralf Scheibner at the University of Würzburg in Germany and co-workers reported a rectification of 11% using a quantum dot – a nano-scale semiconductor device in which the electron wavefunction is localized. Here, the asymmetric flow stems not from the mismatch of resonant frequencies at an interface but from physical differences in the connections between the quantum dot and the two connecting leads: transport is favourable through states with non-zero orbital momentum, therefore leading to large thermal rectification (arXiv:cond-mat/0703514).

One obvious application of the thermal diode is in energy saving. For example, in a tropical country such as Singapore, the outdoor temperature is usually much higher than the indoor temperature, so one would like to prevent heat flowing from outdoors to indoors in order to remain cool inside. During the night, however, the outdoor temperature might be lower than the indoor one, so one would like to allow heat to flow from indoors to outdoors. Currently, air-conditioning is used to maintain a comfortable indoor temperature. But if the walls or windows of buildings were made of thermal diodes, which can automatically increase their heat conduction at night and act as an insulator during the day, huge energy savings could be made.

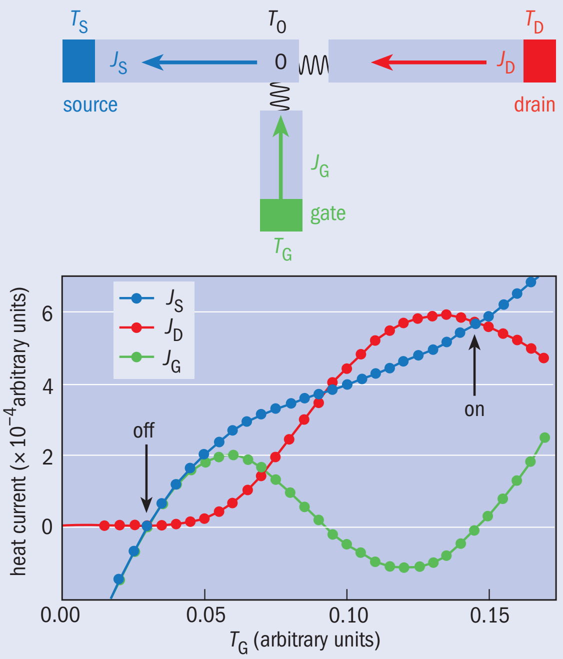
Phononic switching

The thermal diode was a major step towards phononics. But the next big challenge was to build a thermal transistor that could control heat flow like a transistor controls the flow of electric charge. Thermal transistors would greatly improve our ability to control heat flow because they can act as either thermal switches, which turn the heat current "on" and "off", or as modulators that adjust the heat current continuously across a wide range.

Like its electronic counterpart, a thermal transistor has three terminals: the drain, the source and the gate (figure 2). When the temperature at the drain and the source is fixed, the thermal current passing from one to the other is controlled by the temperature at the gate. Importantly, if the transistor is to amplify the signal, then changes in the heat current through the gate need to induce an even larger change from the drain to the source so that the transistor can amplify the signal. But how can we ensure that this condition is met?

It is well known that temperature drops lead to heat currents. When fire meets water, for example, heat flows from the high temperature area to the low temperature area and heats up the water. Generally speaking, the larger the temperature drop, the larger the heat current, which is called a positive differential thermal resistance. However, we found that a thermal transistor can only amplify a heat current if it has a *negative* differential thermal resistance (NDTR), which means

2 Thermal switches and transistors



Like an electronic transistor, a thermal transistor consists of two segments (the source and the drain) as well as a third segment (the gate) through which the input signal is transferred (top). Crucially, negative differential thermal resistance (NDTR) is possible between the source and drain segments, which allows a heat current to be amplified. Calculations reveal that when the gate temperature (T_G) rises, both the drain current (J_D) and the source current (J_S) increase by a factor of almost 100. In particular, the gate current $J_G = J_S - J_D$ is zero when $T_G \approx 0.03$ and $T_G \approx 0.14$. Because the source current is so very different at the two temperatures, we can turn the transistor "off" by making $T_G = 0.03$ and switch it "on" by making $T_G = 0.14$. By making the thermal resistance between the output (O) and the gate very small, the temperature of the output (T_0) is always close to T_G. This switch function means that a thermal transistor can also be used to carry out thermal logic operations such as NOT, AND and OR.

Prototype thermal transistors and thermal logic gates – perhaps even thermal computers – will be available in the near future

that a large temperature drop leads to a small heat current and a small temperature drop leads to a large heat current. NDTR might seem counterintuitive, but it is perfectly possible because heat does still flow from hot to cold. (Negative thermal resistance, whereby heat flows from the cold to the hot, is of course forbidden by the second law of thermodynamics.)

In 2006 we demonstrated NDTR in a system based on the same resonance phenomenon that makes thermal diodes possible, thereby realizing the world's first thermal transistor (*Appl. Phys. Lett.* **88** 143501). The key part of the device consists of a material made up of two segments with different resonant frequencies, similar to that of a thermal diode. In fact, we had already detected a weak NDTR effect when we built the thermal diode, so all we had to do to make a transistor was to adjust the parameters so that the effect was enlarged. This opened the door to building logic gates.

Thermal logic

In an electronic circuit, the two states "1" and "0" are defined by two standard voltages, but in a thermal circuit they are defined by two standard temperatures: T_{on} and T_{off}. The first step towards processing information using heat is therefore to build a "signal repeater", which ensures that whenever the input signal is slightly different from a preset standard temperature, the output is exactly that standard value.

This can be easily achieved in a thermal transistor. When the temperature of the gate, T_G, is close but not exactly equal to either T_{on} or T_{off}, then the direction of the heat current in the gate always makes the temperature in the junction node between the source and the gate closer to either T_{on} or T_{off}. Therefore, by connecting transistors in series, which involves plugging the output of one transistor into the gate of the next one, the final output increasingly resembles a digital signal, i.e. it will either be very near to T_{on} or very near to T_{off}. This laid the foundations for logic gates that together would allow thermal information processing.

In our latest work, we first modelled a NOT gate, which gives out a "1" when it receives "0" and vice versa. To make a thermal NOT gate, therefore, we need the output temperature to fall when the input temperature increases and vice versa. But how can we cool down one part of a system by warming up another part? The answer is to feed the signal from the source segment and collect the output from the drain segment, between which NDTR is possible: a higher temperature in the source segment induces a larger thermal current in the drain and therefore increases the temperature drop. This produces a negative response, and the system therefore serves as a thermal NOT gate.

Next we turned our attention to AND and OR gates, both of which have two inputs and one output. Such gates are easily made by plugging two inputs into the same thermal signal repeater: when both inputs are "1", then the output is also "1"; and when both inputs are "0", then the output is also "0". By simply changing some parameters of the repeaters we were also able to make the final output either "0" or "1" when the two inputs are different, therefore realizing either an AND or an OR gate (*Phys. Rev. Lett.* **99** 177208).

Given the fact that the thermal diode was realized experimentally just two or three years after the theoretical models, prototype thermal transistors and thermal logic gates – perhaps even thermal computers – will be available in the near future. In the meantime, phononics might provide the necessary technology for energy saving.

Of course, there are still a lot of technical problems to be overcome. In particular, phonons travel at speeds of just 1000 m s^{-1} or so – hundreds of thousands of times slower than electromagnetic waves – which means that we have to find some way of maximizing the operational speeds of thermal components if complex thermal networks are to be of any practical use. Even more challenging problems undoubtedly await us *en route* to phononics. ■