An unexpected clue to thermopower efficiency

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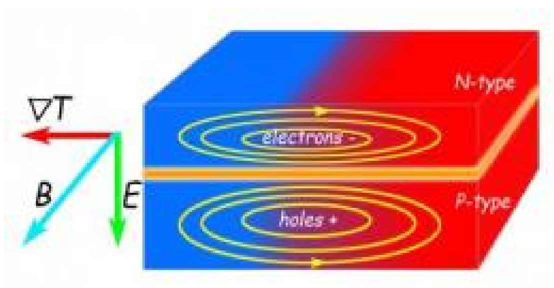

An N-type semiconductor on top of a P-type semiconductor creates a vertical electric field (E, green arrow), while diffusion creates a depletion layer near the junction (orange), where the electric field is strongest. Heating one end of the device creates a heat gradient at right angles to the electric field (del T, red arrow). Electrons and holes moving in these fields are forced into loops of current, and a magnetic field is generated "sideways" (B, blue arrow), at right angles to both electric and thermal fields. Credit: Jinqiao Wu, Lawrence Berkeley National Laboratory

Scientists at the U.S. Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) and their colleagues have discovered a new relation among electric and magnetic fields and differences in temperature, which may lead to more efficient thermoelectric devices that convert heat into electricity or electricity into heat.

"In the search for new sources of energy, thermopower – the ability to convert temperature differences directly into electricity without wasteful intervening steps – is tremendously promising," says Junqiao Wu of Berkeley Lab's Materials Sciences Division (MSD), who led the research team. Wu is also a professor of materials science and engineering at the University of California at Berkeley. "But the new effect we've discovered has been overlooked by the thermopower community, and can greatly affect the efficiency of thermopower and other devices."

Wu and his colleagues found that temperature gradients in semiconductors, when one side of the device is hotter than the opposite side, can produce electronic vortices – whirlpools of electric current – and can, at the same time, create magnetic fields at right angles to both the plane of the swirling electric currents and the direction of the heat gradient. The researchers report their results in *Physical Review B*.

Wu says, "There are four well-known effects that relate thermal, electric, and magnetic fields" – for example, the familiar Hall effect, which describes the voltage difference across an electric conductor in a perpendicular magnetic field – "but in all these effects the magnetic field is an input, not an outcome. We asked, 'Why not use the electric field and the heat gradient as inputs and try to generate a magnetic field?'"

To test the possibilities, the researchers modeled a practical device made of two layers of silicon: a thin, negatively doped layer (N-type) with an excess of electrons and a thicker, positively doped layer (P-type) with an excess of holes, which are electron absences that behave as positively charged particles.

At the junction where the oppositely doped silicon layers meet, a third kind of layer called a P-N junction forms, not physical but electronic: electrons from the N-type layer diffuse across the physical boundary into the P-type layer while holes move in the opposite direction, forming a depletion layer where charges are "dried out".

Given the high density of mobile electrons at the surface of the N-type layer and the high density of mobile holes at the surface of the P-type layer, but few mobile charges in the depletion layer, the electric field is strongest near the junction. This deep layer has profound effects, when a heat gradient is applied to the joined silicon layers.

Wake up and smell the champagne

"There are three ways charges can move – three kinds of currents," says Wu. "One is the diffusion current, in which particles move from denser areas to less dense areas. This has nothing to do with charge. Think of a bottle of champagne. I pop the cork, and a little while later you can smell the champagne, because the molecules diffuse from their dense concentration in the bottle into the air."

The second kind of current is called drift current. "If there's a draft in the room moving toward you, you may smell the champagne a little earlier, or if it's moving away from you, a little later," Wu explains. "In an electronic device, a drift current is caused by the voltage bias, the electric field."

Says Wu, "So in an electronic device we have diffusion current away from the dense charge areas, and drift current due to the electric field, and now we add a third, the thermoelectric current, which is another form of drift current in which charge carriers move from the hotter end of the device to the cooler end."

The results would be uninteresting if all the currents were pointing in the same direction, or in opposite directions, but they're not. The electric field sets up a drift current from the negatively charged top layer toward the positively charged bottom layer of the device – moving against the diffusion currents of the charge carriers. Meanwhile the heat gradient sets up a drift current at right angles to the electric field.

"In these conflicting perpendicular forces, electrons and holes cannot maintain straight motion but are sucked into vortices," Wu says.

Instead of a single vertical vortex in the device, vortices form in each layer and are separated by the depletion layer. In the N-type layer, the widely separated electrons near the depletion layer move with the temperature gradient, from hot to cold, but move in the opposite direction near the surface, where the electrons are bunched closer together. The vortex formed by holes in the N-type layer is nearly a mirror image of the electron vortex.

The unusual result is that merely by applying heat to one end of a simple silicon device, the researchers can generate a magnetic field perpendicular to the twin vortices – a magnetic field that emerges at right angles to the plane of the two silicon layers.

"The immediate application is not that we can make a magnetic field, which is relatively weak, but the realization that the efficiency of many semiconductor devices, including commercial products, could be made more efficient if we do it right," Wu says. "For example, designing them to make sure that their electric fields, and inhomogeneities in composition or doping, are aligned with their heat gradients would avoid these energy-wasting current vortices."

Wu's fascination with the new effect he and his teammates discovered doesn't stop there, however. "My interest isn't just in making more efficient electronics but in making good things out of this. The first step is to confirm with experiment what we've discovered through modeling. After that, a whole new program of research opens up."

Wu explains that the remarkable electronic and magnetic effects caused by temperature differences in the current model may well be duplicated by other kinds of inhomogeneous excitation – for example, by the way light falls on a solar cell. "Different intensities or different wavelengths falling in different areas of a photovoltaic device will produce the same kinds of electronic vortices and could affect solar cell efficiency. Understanding this effect may be a good path to better efficiency in electronics, thermal power, and solar energy as well."

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