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MATERIALS SCIENCE

Chain mail reverses the Hall effect

The sign of a material's charge carriers is usually reflected in the sign of the 'Hall voltage'. But for a structure inspired by chain mail, altering its geometry inverts the Hall voltage, even if the charge carriers are unchanged.

MASAYA NOTOMI

In 1879, the physicist Edwin Hall made a remarkable discovery[1]. He found that when a magnetic field is applied to a conducting material that has an electric current flowing perpendicular to the field, a voltage is generated that is perpendicular to both the current and the field. The sign of this voltage reflects the sign of the charges responsible for the current — a fact that has been widely used in various applications in solid-state physics. More than a century later, the Hall effect serves as the basis of many exotic physical phenomena, including the quantum Hall effect[2], the spin Hall effect[3] and even the Hall effect of light[4]. Writing in *Physical Review Letters*, Kern *et al.*[5] report yet another unusual phenomenon related to the Hall effect. The authors show that the sign of the Hall voltage is inverted in a 3D structure inspired by chain mail, a type of armour consisting of small metal rings linked together to form a mesh, used since ancient times.

The authors' chain-mail structure belongs to a certain class of metamaterial — artificial structures whose electromagnetic properties differ drastically from those of the materials that comprise them. In the past two decades, it has been demonstrated that metamaterials can switch from having positive to negative electromagnetic coefficients. These coefficients include the dielectric constant, permeability and refractive index, all of which had previously been considered to be intrinsic properties of a material[6]. For example, negative refraction leads to various counter-intuitive phenomena, such as a superlens that can produce images that have a resolution beyond the diffraction limit of an ordinary lens.

The macroscopic properties of conventional metamaterials generally arise from an alternating current (a.c.) — a time-dependent response of conducting electrons in the materials' smallest repeating units (unit cells) to an electromagnetic field. For these materials, it is therefore essential that their unit cells are smaller than the wavelength of the electromagnetic waves. A wide variety of such metamaterials have been designed whose a.c. response can be substantially changed. By contrast, the Hall effect is a direct current (d.c.) phenomenon involving a current and an electromagnetic field that have a constant magnitude, which means that the wavelength of the electromagnetic waves is essentially infinite. Kern and colleagues design their metamaterial to alter this d.c. response.

In 2009, it was proposed[7] that a 3D chain-mail structure could generate an inverted Hall voltage. Kern *et al.* produce a modified version of this original design using a combination of sophisticated 3D laser-sculpting technology and a technique allowing the deposition of atomically thin layers of coatings. The authors' metamaterial consists of microscale rings made of a polymer coated with zinc oxide. The zinc oxide is n-doped, which

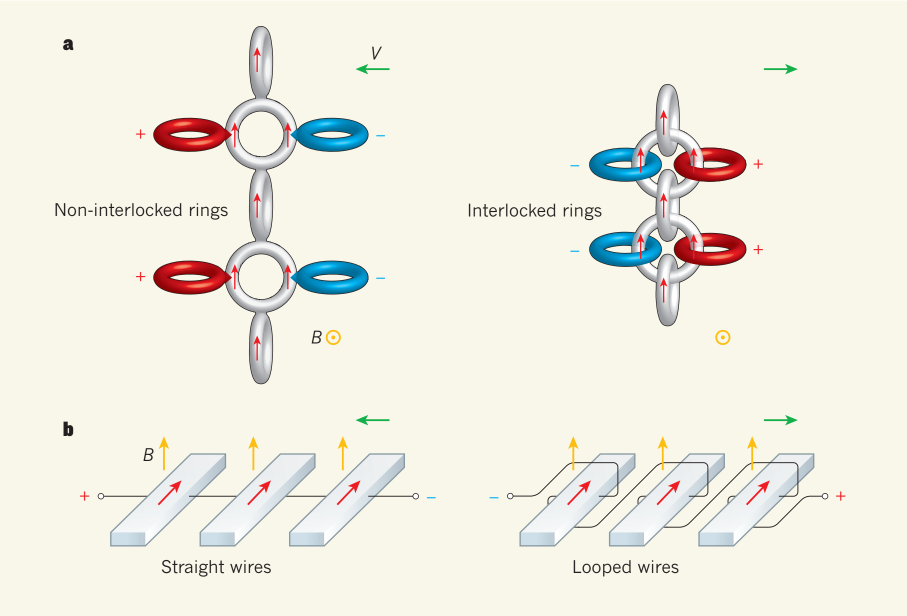

Figure 1 | Reversing the Hall voltage. Kern *et al.*[5] have constructed a 3D material consisting of microscale rings made of a polymer coated with zinc oxide. The zinc oxide is n-doped, which means that electrical transport occurs through negatively charged carriers. **a**, Shown here is a simplified illustration of the material's structure, in which there is a current (red arrows) passing through the grey rings and a magnetic field (B) perpendicular to the plane of the page. When the rings are not interlocked, a voltage, called a Hall voltage (V), is observed passing from the negatively charged blue rings to the positively charged red rings, in the expected direction. But when the rings are interlocked, a Hall voltage is observed in the opposite direction. **b**, Kern and colleagues' observations can be explained by considering a simple system consisting of an array of conducting bars connected by electrical wires (black lines) and placed in a magnetic field. When the bars are connected by straight wires (analogous to non-interlocked rings), a conventional Hall voltage is generated. But when they are connected by looped wires (analogous to interlocked rings), the voltage is inverted.

means that electrical transport occurs through negatively charged carriers. Naively, one might expect that the unit cells of the authors' d.c. metamaterial can be arbitrarily large because the wavelength of the electromagnetic waves is infinite, implying that microfabrication is not required. However, microscale units are essential because the Hall voltage is inversely proportional to the thickness of the conducting material.

By applying a magnetic field of 0.83 tesla and a current of 0.5 milliamps to their metamaterial, the authors measure a positive Hall voltage of about 70 microvolts. The sign of this voltage is opposite to that expected from the negatively charged carriers in n-doped zinc oxide. The authors also show that the sign and amplitude of the Hall voltage can be altered by modifying the structure's geometry (Fig. 1a). When the individual rings are not interlocked, the Hall voltage is negative (consistent with the negatively charged carriers in n-doped zinc oxide), but when the rings are interlocked, this voltage is inverted.

The fact that the sign of the Hall voltage is determined by the topology of rings is reminiscent of topological insulators[8] and their photonic counterpart[9], in which electronic and photonic properties, respectively, are strongly dependent on the underlying topology. Although the inherent physics is fundamentally different, the authors' chain-mail metamaterial is another example of how geometrical connectivity can affect an electromagnetic response. It has also been demonstrated that another material property, the coefficient of thermal expansion, can be negative if the topology of an artificial composite with multiple phases is carefully designed[10].

The basic mechanism underlying Kern and collaborators' observations can be understood by considering a simple system consisting of three conducting bars connected by electrical wires and placed in a magnetic field (Fig. 1b). In such a system, the sign of the Hall voltage depends on how the wires are connected to the bars, but an additional Hall voltage arises from the wires themselves. In the authors' 3D metamaterial, this additional voltage is eliminated because each ring is perpendicular to the rings connected to it, which leads to an isotropic, macroscopic electromagnetic response.

This simplified model clarifies how the authors' metamaterial works. The direction of the macroscopic voltage and current can be altered independently of the direction of the local electromagnetic response, owing to the topology of the material's conductive network.

Kern and colleagues' observed Hall voltage is small compared with the transverse voltage that arises from the slight asymmetry in the fabricated material, and any immediate applications for their findings are not obvious. However, the authors' work could pave the way for new research directions in the study of metamaterials, and might lead to other artificially designed metamaterials whose macroscopic electromagnetic response can be radically changed owing to an elaborately arranged internal connectivity. ■

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BIOCHEMISTRY

A wine-induced breakdown

A polysaccharide called rhamnogalacturonan II is a major component of some fruits, but humans rely on their gut microbiota to digest it. The microbes and processes responsible for this digestion have now been revealed. SEE ARTICLE P.65

MIRJAM CZJZEK

When you sip a glass of wine, you might be feeding some of your gut bacteria their favourite food: a polysaccharide named rhamnogalacturonan II (RGII). This is because humans do not produce the enzymes needed to break down most of the polysaccharides in plant-based food[1] into single sugar molecules, whereas some bacteria in the human gut flora (the microbiota) do. But precisely how the complex components of fruit cell walls, such as RGII, are decomposed in the human gut, and which microbes are responsible, was not known. Ndeh *et al.*[2] report on page 65 that, surprisingly, bacterial consortia are not required — single bacterial strains common in most human gut microbiota possess the entire enzymatic system needed to break down and metabolize RGII.

It has become clear that human nutrition affects the diversity of the gut microbiota and directly influences health[3]. But many questions remain about the interplay of different microbial strains in polysaccharide digestion and the underlying molecular mechanisms. RGII, for example, constitutes up to 15% of the cell-wall components of some fruit, particularly grapes. Do different types of mutually beneficial microbes work together to cleave the 21 types of glycosidic bond that connect the individual sugars in RGII (ref. 4) from grapes? Or have highly specialized bacterial phyla developed an enzyme system that breaks down all the bonds?

Ndeh and colleagues used a combination of biochemical, crystallographic and microbial studies to work out the key mechanistic and functional aspects of RGII decomposition. Their detailed analyses led to the discovery of seven families of glycoside hydrolase enzymes (GHs) that cleave glycosidic bonds for substrates that were not known to be cleaved by GHs. They also report several previously unknown substrate specificities for existing GH families. Strikingly, the authors' detailed study of the specificity and mode of action of the newly discovered enzymes reveals that some of the chemical structures thought to be present in RGII were incorrect (Fig. 1).

The tremendous complexity of naturally occurring polysaccharides is one of the main reasons why the biochemical characterization of these compounds still lags far behind that of other naturally occurring polymers. The polysaccharide 'alphabet' is much more complicated than those of DNA or proteins, consisting of about 120 naturally occurring monosaccharides that can be linked and branched in many ways. We do not yet have the methods and techniques to easily access the sequences and detailed structures of polysaccharides, so such analyses remain difficult and time-consuming.

One approach that helps to simplify sequencing and structure determinations, and that was used by Ndeh *et al.* in their study, is to expose polysaccharides to GHs that break a known type of glycosidic bond. Characterization of the products of several different GH