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Semiconductor metamaterial fools the Hall effect FREE

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Physics Today **70** (2), 21–23 (2017);
https://doi.org/10.1063/PT.3.3453

liquid theories, that isn't terribly surprising. To precisely control the thickness and structure of their water films, the PNNL researchers performed their experiments under vacuum. Although some two-liquid theories predict a first-order phase transition at vacuum pressures (see the blue curve in figure 2), most predict that the liquid–liquid equilibrium curve extends down only to a critical point located at several hundred times atmospheric pressure (red curve). To test those scenarios, the PNNL group would have to adapt its technique for high-pressure operation, a task that Kay says "would be tricky, but possibly doable."

For now, the researchers have set their eyes on a different experimental prize: measuring the homogeneous nucleation rate of water throughout no-man's-land—data that would provide a coveted benchmark for numerical models.

Ashley G. Smart

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Semiconductor metamaterial fools the Hall effect

A structure made entirely out of an n-type semiconductor can mimic some properties of a p-type semiconductor.

Much to the confusion of many beginning physics students, electric current vectors are conventionally written as if they represented the flow of positive charge: The direction of the current is opposite to the direction in which electrons actually move. The convention has its origins in Benjamin Franklin's one-fluid theory of electricity. Lacking evidence to the contrary, Franklin assumed that the phenomena he observed resulted from the movement of a positive "electric fire." The theory was mostly serviceable: There's often little to distinguish a positive charge moving in one direction from a negative charge moving in the other.

One way to tell the difference is via the Hall effect, the appearance of a transverse voltage when an electric current passes through a magnetic field. Charge carriers are deflected in the direction that corresponds to the cross product of the (conventionally written) current and the field. If the charge carriers are positive, they produce a voltage gradient in the same direction. If they're negative, the gradient is in the opposite direction.

The Hall effect provides experimental evidence that currents in metals arise from the flow of negative charge. It also offers a way to distinguish between n-type semiconductors, whose charge carriers are also electrons, and p-type semiconductors, whose charge carriers are positively charged holes.

But the relationship between charge-carrier sign and Hall voltage is not always so simple, as Martin Wegener and his colleagues at the Karlsruhe Institute of Technology in Germany have now experimentally shown.[1] Using an n-type semiconductor, the researchers crafted a microstructured metamaterial, shown in figure 1, that behaves like a p-type semiconductor—at least as far as the Hall effect is concerned.

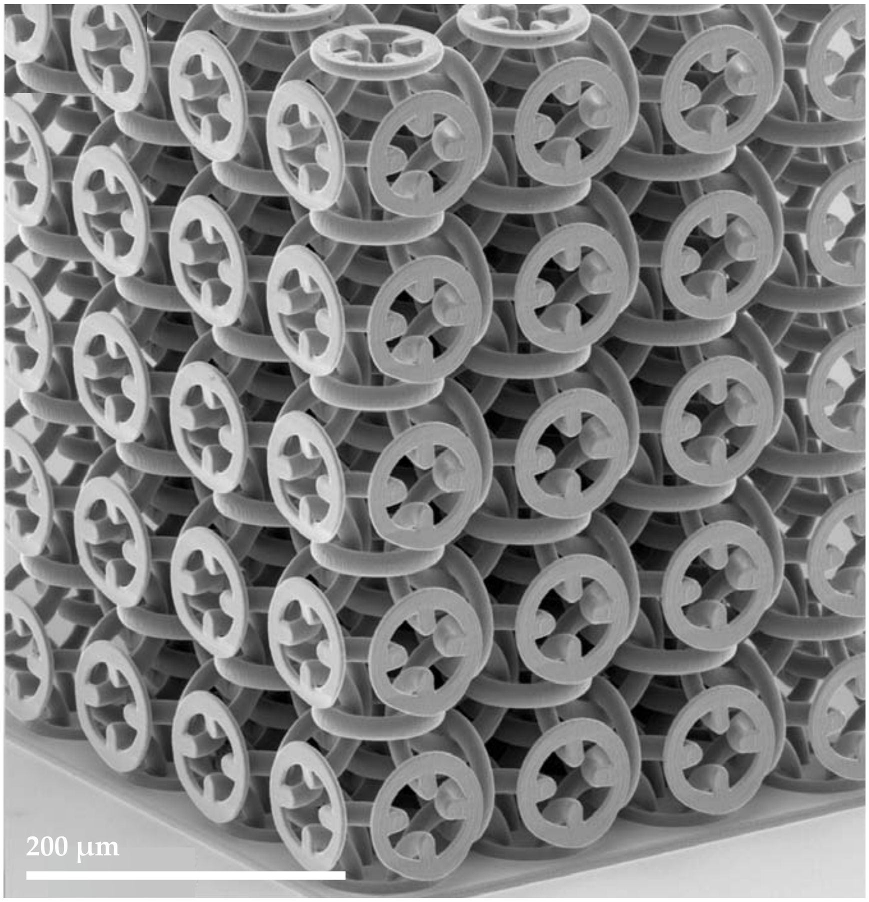

FIGURE 1. INSPIRED BY MEDIEVAL ARMOR. The metamaterial shown in this electron micrograph is a periodic array of linked hollow rings. Made of n-type zinc oxide, it exhibits the Hall signature of a p-type material. (Adapted from ref. 1.)

Science mirrors art

The literature is full of examples of metamaterials with electromagnetic, acoustic, or mechanical properties that are qualitatively different from those of their constituents. For example, metamaterials can be designed to have both negative electric permittivity and negative magnetic permeability (or, more simply, a negative index of refraction), despite the fact that there are no such bulk materials in nature.

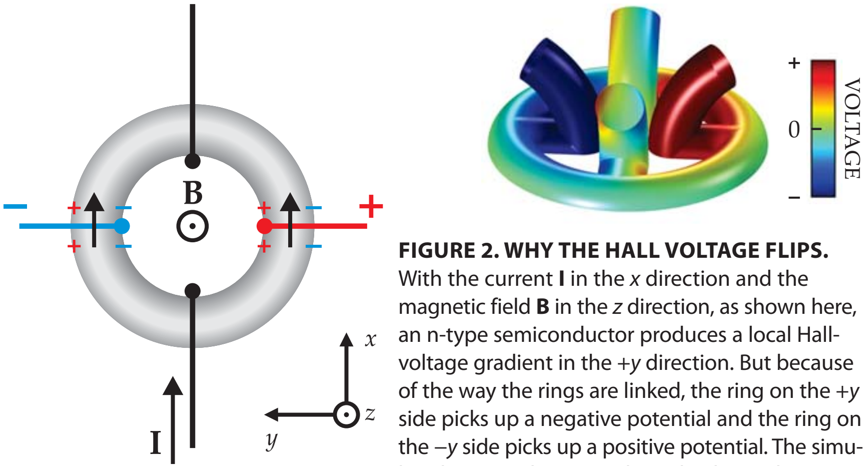

FIGURE 2. WHY THE HALL VOLTAGE FLIPS. With the current **I** in the *x* direction and the magnetic field **B** in the *z* direction, as shown here, an n-type semiconductor produces a local Hall-voltage gradient in the +*y* direction. But because of the way the rings are linked, the ring on the +*y* side picks up a negative potential and the ring on the −*y* side picks up a positive potential. The simulated potential map on the right shows the same region in more detail. (Adapted from refs. 1 and 3.)

That tunability of electromagnetic properties can be exploited to create an invisibility cloak: a metamaterial shell that bends electromagnetic waves in a way that leaves no trace of the cloak itself or any objects it conceals. (See PHYSICS TODAY, February 2007, page 19.) Unfortunately, the effect isn't quite as striking in real life as it is in the fictional *Star Trek* or *Harry Potter* universes. Cloaking metamaterials are made up of tiny resonators that function only over a limited frequency range. To reveal an invisibility cloak, all you need to do is illuminate it with a different color light. Most other curious metamaterial behaviors also arise from internal resonances, so they're also frequency dependent.

The Hall-effect inversion is different. Rather than relying on an oscillation of just the right frequency, it works with direct current. As pointed out by the University of Utah's Graeme Milton, one of the mathematicians who predicted the effect, the fact that an n-type metamaterial can so effectively mimic a p-type base material "shows some limitations on what information we can gain about what's really inside a three-dimensional body."

Milton and his collaborator Marc Briane came up with the idea of Hall-effect inversion while working with Vincenzo Nesi on a different but related problem: the effective conductivity of a composite material under a static nonzero electric field but no magnetic field. They rigorously proved that it was possible for certain properties of the conductivity to change sign in a 3D composite but not in a 2D composite. The same turned out to be true for the Hall voltage.

Milton and Briane were exploring the electromagnetic properties of 2D arrays of interlocked rings resembling medieval chain-mail armor when they happened upon the website of a chain-mail artist named Dylon Whyte. Briane sought Whyte's permission to reproduce one of his artistic images in a paper. In his reply, Whyte suggested a 3D interlocking ring structure for the mathematicians to consider. "That turned out to be precisely what we needed!" says Milton: He and Briane showed theoretically in 2009 that a version of Whyte's structure, made entirely of n-type materials, had the Hall properties of a p-type semiconductor.[2]

Forging links

Briane and Milton's metamaterial required three distinct n-type materials: one for the rings themselves, one to form bridges between linked rings, and one background material in which the whole structure was embedded. Creating such a metamaterial in the lab—on the micron scale and with the necessary precision of all the material interfaces—would have been unreasonably demanding.

But two years ago, while tinkering with numerical simulations of Hall-effect inversions, Wegener's postdoc Muamer Kadic found that the structure could be simplified to require only one semiconducting material.[3] (The unit cell of the simulated structure is shown on the cover of this issue.) That simplification brought fabrication within reach.

The fabrication effort, led by PhD student Christian Kern, began with 3D direct laser writing—a form of 3D printing—to make a scaffold structure out of a polymer material. The scaffold was then coated with a thin film of n-type zinc oxide, a wide-bandgap semiconductor. Removing the scaffold was unnecessary: Because it's electrically insulating, it has no effect on the metamaterial's electrical properties. The interlocked rings were essentially hollow tubes rather than solid tori—but according to simulations, that geometry doesn't change the qualitative behavior.

Theory was borne out by experiment: The n-type ZnO metamaterial produced the Hall voltage of a p-type semiconductor. For a qualitative picture of what's going on, consider the sketch in figure 2. With the current in the $+x$ direction and the magnetic field in the $+z$ direction, the Hall effect in an n-type material normally produces a positive potential on the $+y$ side (toward the left in the figure) and a negative potential on the $-y$ side. Indeed, that's still the case locally for small regions of material, such as the vicinities of the small black arrows. However, because the currents and voltages are passed from ring to ring via the rings' inner edges, the ring on the left picks up a negative potential and the ring on the right picks up a positive potential. Compounded across the 5-unit-cell width of the metamaterial, the effect gives a measurable inverted Hall voltage on the order of 50 μV from a current of 0.5 mA and a magnetic field of 0.83 T.

It's not yet clear what applications, if any, the Hall-effect inversion might have. Just because the metamaterial behaves like a p-type semiconductor doesn't mean it is one. "The charge carriers still carry negative charge," says Kern, so the metamaterial can't replace the p-type material in a semiconductor diode, for example. And even if it could, p-type semiconductors are readily available, so there'd be no obvious advantage to the replacement.

Still, Wegener and his group are pressing onward. They're working on the technical challenges of interfacing their metamaterial with a silicon chip, to study the effect in more detail and possibly exploit it in a magnetic field sensor. And they're looking into anisotropic metamaterials, which can produce a Hall-voltage gradient with a component parallel to the magnetic field—another effect not found in nature.

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PHYSICS UPDATE

These items, with supplementary material, first appeared at www.physicstoday.org.

SUPERLUMINOUS EVENT MAY LOSE SUPERNOVA STATUS

In June 2015 the All-Sky Automated Survey for Supernovae snagged a huge fish: an extremely luminous object, dubbed ASASSN-15lh, whose spectrum appeared consistent with that of a supernova. The object's luminosity peaked at about 2.2×10^{45} erg/s (2.2×10^{38} J/s), a factor of two higher than that of any other measured stellar explosion (see PHYSICS TODAY, March 2016, page 14). Yet the ramifications of the supernova interpretation, including the sheer scale of nucleosynthesis necessary to generate so much energy, led scientists to consider alternative mechanisms.

Following a 10-month examination at multiple wavebands, one research team now argues that ASASSN-15lh is actually a star that got torn apart by the extreme tidal forces of its galaxy's supermassive black hole (SMBH). The scientists, led by Giorgos Leloudas from the Weizmann Institute of Science in Israel and the University of Copenhagen in Denmark, found that ASASSN-15lh went through three distinct spectroscopic phases, including one with helium emission lines that have never been detected in the brightest supernovae. Further support for the researchers' proposal comes from the location of ASASSN-15lh. The event took place at the center of a massive red galaxy whose star formation rate has all but petered out. Such galaxies harbor SMBHs but not the young blue stars whose lives end in supernovae. The researchers also observed a second peak in UV emissions about two months after ASASSN-15lh, which is consistent with the behavior of a previous transient that is thought to be a tidal disruption event.


ESO, ESA/HUBBLE, M. KORNMESSER

In making their case, Leloudas and colleagues faced one major objection: The SMBH in question is so massive that it should swallow stars whole rather than shredding them first. The researchers circumvented that problem by proposing that the black hole is rapidly spinning (see artist's conception here), which can extend the range of strong tidal forces by nearly an order of magnitude. (G. Leloudas et al., *Nat. Astron.* **1**, 2, 2016.) —AG

CONSTRAINING INTERPRETATIONS OF QUANTUM MECHANICS

John Stewart Bell's famous theorem is a statement about the nature of any theory whose predictions are compatible with those of quantum mechanics: If the theory is governed by hidden variables, unknown parameters that determine the results of measurements, it must also admit action at a distance. Now an international collaboration led by Adán Cabello has invoked a fundamental thermodynamics result, the Landauer erasure principle, to show that systems in hidden-variable theories must have an infinite memory to be compatible with quantum mechanics.

In quantum mechanics, measurements made at an experimenter's whim cause a system to change its state; for a two-state electron system, for example, that change can be from spin up in the z-direction to spin down in the x-direction. Because of those changes, a system with hidden variables has to have a memory so that it knows how to respond to a series of measurements; if that memory is finite, it can serve only for a limited time. As an experimenter keeps making observations, the system must eventually update its memory, and according to the Landauer principle, the erasure of information associated with that update generates heat. (See the article by Eric Lutz and Sergio