Penn metamaterials experts show a way to reduce electrons' effective mass to nearly 0

PHILADELPHIA — The field of metamaterials involves augmenting materials with specially designed patterns, enabling those materials to manipulate electromagnetic waves and fields in previously impossible ways. Now, researchers from the University of Pennsylvania have come up with a theory for moving this phenomenon onto the quantum scale, laying out blueprints for materials where electrons have nearly zero effective mass.

Such materials could make for faster circuits with novel properties.

The work was conducted by Nader Engheta, the H. Nedwill Ramsey Professor of Electrical and Systems Engineering in Penn's School of Engineering and Applied Science, and Mario G. Silveirinha, who was a visiting scholar at the Engineering School when their collaboration began. He is currently an associate professor at the University of Coimbra, Portugal.

Their paper was published in the journal *Physical Review B: Rapid Communications*.

Their idea was born out of the similarities and analogies between the mathematics that govern electromagnetic waves — Maxwell's Equations — and those that govern the quantum mechanics of electrons — Schrödinger's Equations.

On the electromagnetic side, inspiration came from work the two researchers had done on metamaterials that manipulate permittivity, a trait of materials related to their reaction to electric fields. They theorized that, by alternating between thin layers of materials with positive and negative permittivity, they could construct a bulk metamaterial with an effective permittivity at or near zero. Critically, this property is only achieved when an electromagnetic wave passes through the layers head on, against the grain of the stack. This directional dependence, known as anisotropy, has practical applications.

The researchers saw parallels between this phenomenon and the electron transport behavior demonstrated in Leo Esaki's Nobel Prize-winning work on superlattices in the 1970s: semiconductors constructed out of alternating layers of materials, much like the permittivity-altering metamaterial.

A semiconductor's qualities stem from the lattice-like pattern its constituent atoms are arranged in; an electron must navigate the electric potentials of all of these atoms, moving faster or slower depending on how directly it can pass by them. Esaki and his colleagues showed that, by making a superlattice out of layers of different materials, they could produce a composite material that had different electron transport properties than either of the components.

Though the actual mass of electrons is fixed, Engheta and Silveirinha thought the same principle could be applied to the effective mass of the electron. Engineers have been tailoring materials to alter the effective mass of electrons for decades; existing semiconductors that give electrons a negative effective mass were a prerequisite for the team's new theory.

"Imagine you have a ball inside a fluid," Engheta said. "You can calculate how fast the ball falls as a combination of the force of gravity and the reaction of the fluid, or you can say that the ball has an effectively different mass in the fluid than it does normally. The effective mass can even be negative, which we see in the case of a bubble. The bubble looks like it has negative mass, because it's moving against gravity, but it is really the fluid moving down around it."

Like the optical metamaterial with alternating bands of positive and negative permittivity, Engheta and Silveirinha theorized, a material with alternating bands of positive and negative effective electron mass would allow the overall structure's effective electron mass to approach zero.

And like the optical metamaterial, the electron's effective mass in this case would be anisotropic. While travelling against the grain of the alternating materials, its effective mass would be near-zero, and thus it would travel very fast. But trying to move the electron along the grain would result in a very high effective mass, making it very difficult for it to move at all. "In the direction the electrons are collimated, we see an effective mass of zero," Engheta said. "This is like what we see with graphene, where electrons have an effective mass of zero but only along its plane.

"But a plane of graphene is only one atom thick, whereas here we would see that property in a bulk material. It's essentially like the material has wires running through it, even though there is no wire surface."

As with graphene, the properties of this composite material would be dependent on structure at the smallest scale; a few stray atoms could significantly degrade the material's overall performance. A single uniform layer of atoms is ideal in both cases, and, while deposition techniques are improving, working at the scale of a few nanometers still represents a physical challenge. The team hopes to address this challenge in future studies.

"While physics prevents us from having infinite velocity, having materials that give electrons near-zero effective mass will let us move them much faster," Engheta said.

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