The onset of electrical resistance

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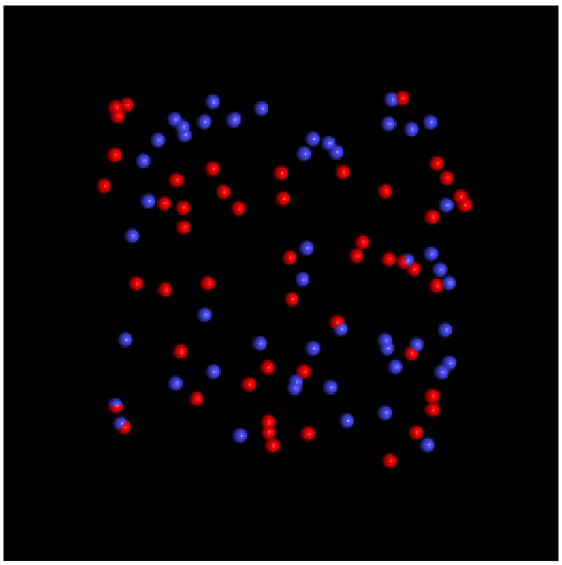

Electrons (blue balls) and holes (red balls) show random thermal motion before the terahertz pulse hits the sample. Copyright: MBI

Researchers at the Max-Born-Institute, Berlin, Germany, observed the extremely fast onset of electrical resistance in a semiconductor by following electron motions in real-time.

When you first learned about electric currents, you may have asked how the electrons in a solid material move from the negative to the positive terminal. In principle, they could move ballistically or 'fly' through the solid, without being affected by the atoms or other charges of the material. But this actually never happens under normal conditions because the electrons interact with the vibrating atoms or with impurities. These collisions typically occur within an extremely short time, usually about 100 femtoseconds (10^{-13} seconds, or a tenth of a trillionth of a second). So the electron motion along the material, rather than being like running down an empty street, is more like trying to walk through a very dense crowd. Typically, electrons move only with a speed of 1m per hour, they are slower than snails.

Though the electrons collide with something very frequently in the material, these collisions do take a finite time to occur. Just like if you are walking through a crowd, sometimes there are small empty spaces where you can walk a little faster for a short distance. If it were possible to follow the electrons on an extremely fast (femtosecond) time scale, then you would expect to see that when the battery is first turned on, for a very short time, the electrons really do fly unperturbed through the material before they bump into anything.

This is exactly what scientists at the Max-Born-Institute in Berlin recently did in a semiconductor material and report in the current issue of the journal *Physical Review Letters* [volume 107, 256602 (2011)]. Extremely short bursts of terahertz light (1 terahertz = 10^{12} Hz, 1 trillion oscillations per second) were used instead of the battery (light has an electric field, just like a battery) to accelerate optically generated free electrons in a piece of gallium arsenide. The accelerated electrons generate another electric field, which, if measured with femtosecond time resolution, indicates exactly what they are doing. The researchers saw that the electrons travelled unperturbed in the direction of the electric field when the battery was first turned on. About 300 femtoseconds later, their velocity slowed down due to collisions.

In the attached movie, we show a cartoon of what is happening in the gallium arsenide crystal. Electrons (blue balls) and holes (red balls) show random thermal motion before the terahertz pulse hits the sample. The electric field (green arrow) accelerates electrons and holes in opposite directions. After onset of scattering this motion is slowed down and results in a heated electron-hole gas, i.e., in faster thermal motion.

The present experiments allowed the researchers to determine which type of collision is mainly responsible for the velocity loss. Interestingly, they found that the main collision partners were not atomic vibrations but positively charged particles called holes. A hole is just a missing electron in the valence band of the semiconductor, which can itself be viewed as a positively charged particle with a mass 6 times higher than the electron. Optical excitation of the semiconductor generates both free electrons and holes which the terahertz bursts, our battery, move in opposite directions. Because the holes have such a large mass, they do not move very fast, but they do get in the way of the electrons, making them slower.

Such a direct understanding of electric friction will be useful in the future for designing more efficient and faster electronics, and perhaps for finding new tricks to reduce electrical resistance.

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