Universität Regensburg

A long-distance relationship within femtoseconds

Electron-hole pairs can drift apart at ultrafast speed while staying strongly bound

Modern electronics relies on ultrafast charge motion on ever shorter length scales. Physicists from Regensburg and Gothenburg have now succeeded in resolving a key quantum motion of electrons in atomically thin crystals on the time scale of a single oscillation cycle of light. They directly observe, how the electron in a bound electron-hole pair jumps from one atomic layer to the next, creating a long-distance relationship, called an "interlayer exciton". The results have been published in the top-tier journal *Nature Materials*.

Fast electronics requires compact circuits; the limit is the atomic length scale. Novel, layered crystals of so-called transition metal dichalcogenides, which can be thinned down to a few atomic layers, promise ultimately thin components such as solar cells and transistors. However, electrons behave very unconventionally if confined into two dimensions. For example, if an electron is excited by light in a transition metal dichalcogenide, it can leave behind a hole at its original place. Electron and hole can form a bound pair, an exciton, in which the negatively charged electron orbits the positively charged hole like an electron in the hydrogen atom orbiting the nucleus. Because of the strong attraction between electrons and holes, these excitons are stable even at room temperature.

For important applications, such as solar cells, however, electrons and holes need to be spatially separated. This is achieved by stacking two different dichalcogenides on top of each other. Physicists from Regensburg led by Rupert Huber, Tobias Korn, John Lupton, and Christian Schüller in collaboration with Ermin Malic's group at Chalmers University in Sweden have now observed this charge separation of excitons across two atomically thin layers. They excited electrons by ultrashort light pulses creating excitons selectively in one of the two layers. If these excitons remain within this layer, they are very short-lived, because the electron can rapidly return to its initial position. In a layered sample structure, in contrast, the electron can hop into the adjacent layer, such that a spatially separated, so-called interlayer exciton emerges.

"Since the layers are atomically thin, the electron still feels the presence of the hole and the two can continue interacting across the layers," explains Fabian Mooshammer, PhD student and co-author of the study. Due to the spatial separation, however, it takes much longer for the electron to return to its initial position. The extended lifetime is only one of the reasons why interlayer excitons have caused tremendous excitement in recent years, both in fundamental research and in optoelectronics.

The scientists managed to observe the behavior of these interlayer excitons during and after their formation. They used a home-built super slow-motion camera to study processes taking place within a few femtoseconds - the millionth part of a billionth of a second. "For the first time, we resolved the formation process of an interlayer exciton and measured how strongly electrons and holes remain bound," says Philipp Merkl, first author of the publication. In addition, the researchers were able to systematically influence the dynamics of the formation process. They used another special feature of the layered heterostructures, twisting the two layers with respect to each other. This changes the electronic and optical properties of the resulting structure, which in turn governs the charge transfer.

These findings represent an important milestone in the development of novel, custom-tailored layered structures and could pave the way for a new generation of ultimately compact and efficient electronics, optoelectronics and information technologies.

Original publication:
P. Merkl, F. Mooshammer, P. Steinleitner, A. Girnghuber, K.-Q. Lin, P. Nagler, J. Holler, C. Schüller, J. M. Lupton, T. Korn, S. Ovesen, S. Brem, E. Malic and R. Huber,
"Ultrafast transition between exciton phases in van der Waals heterostructures",
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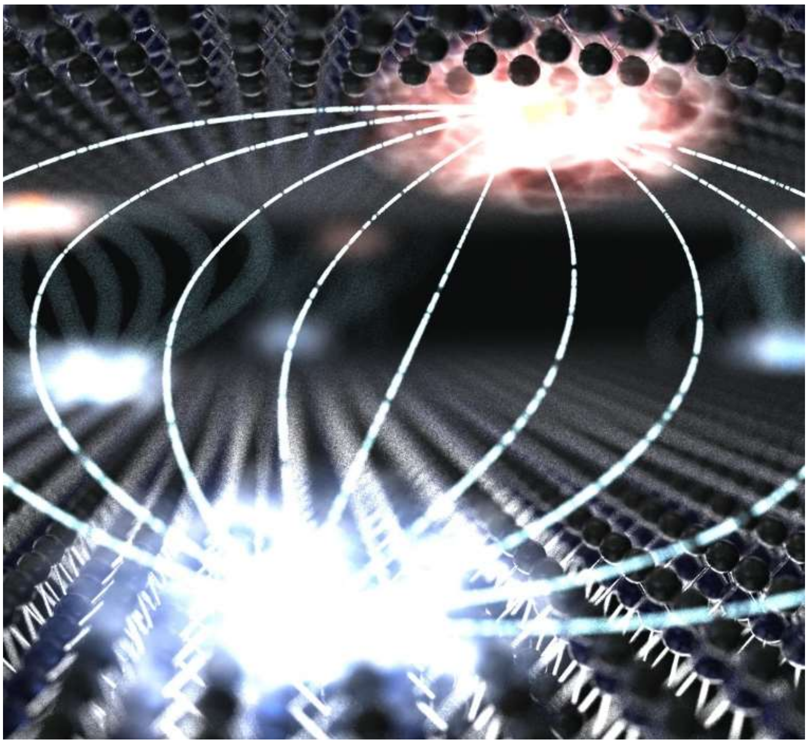

Figure caption:
Artistic representation of an interlayer exciton in a layered structure of monolayer transition metal dichalcogenides. The electron (blue) and the hole (red) interact across the atomic distance, illustrated by the white field lines. Illustration: Brad Baxley (parttowhole.com)

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