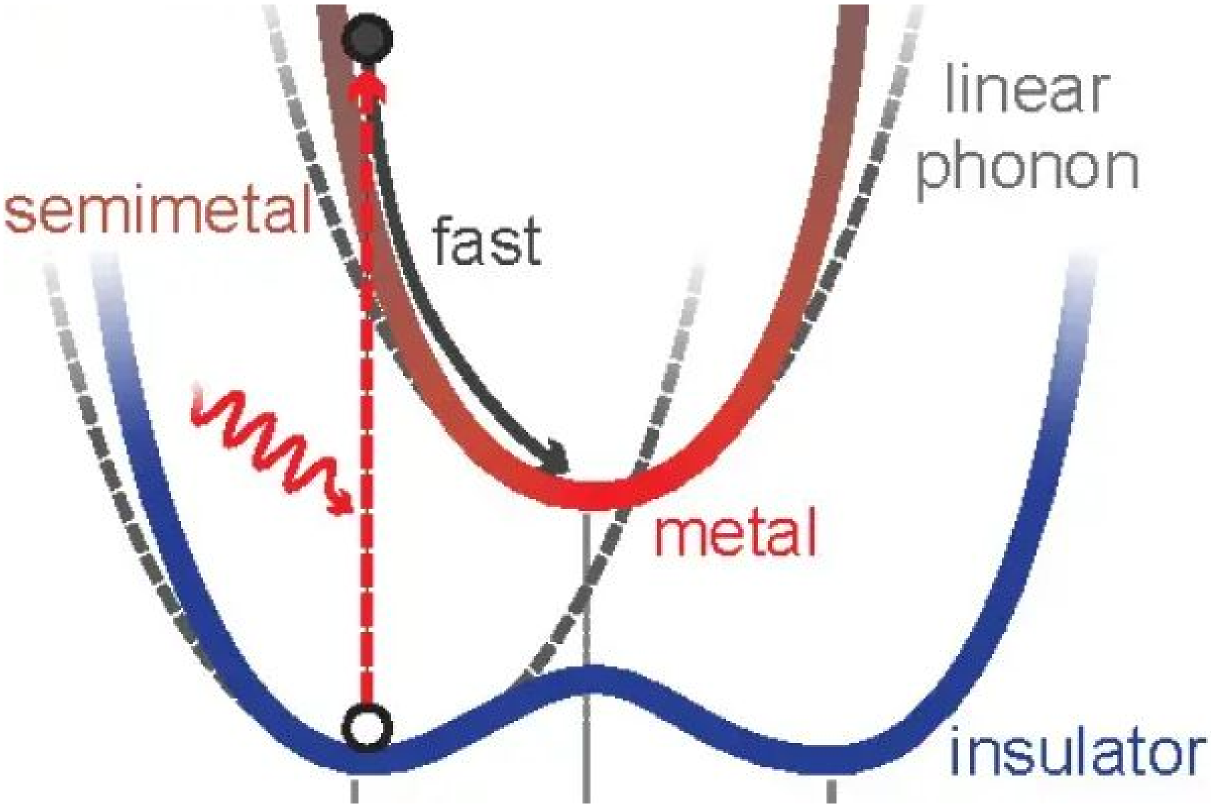

Unraveling the ultrafast phase transition of vanadium dioxide

Researchers uncover the whole pathway that vanadium dioxide undertakes during the light-induced phase transition from insulator to metal. The proposed technique could reveal hidden complexities in similar transitions of other quantum materials.

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Understanding which interactions at the atomic and subatomic level underlie the features of quantum materials can be incredibly challenging. Vanadium dioxide (VO2) and its ultrafast phase transition from insulator to metal exemplifies this complexity. For over 50 years it has been debated whether this transition is driven by electronic changes (that is, modifications to the material's energy ?landscape', or band structure) or structural changes (alterations in how the atomic lattice is arranged).

Now, for the first time, a team of researchers led by Heriot-Watt University and IMDEA Nanoscience, with the collaboration of ICFO researchers **Dr. Lin Zhang**, **Dr. Utso Bhattacharya**, **Maria Recasens**, **Dr. Johann Osmond**, and **ICREA Prof. Maciej Lewenstein**, has directly observed both structural and electronic transitions in VO2. They have discovered that the electronic transformation triggers the structural one, in an intricate process that unfolds in under 100 femtoseconds. In the study, which has been published in Nature Communications, several other institutions have participated, including the University of Memphis, ETH Zurich, Donostia International Physics Center, Adam Mickiewicz University, and Vanderbilt University. Until now, previous experiments had only been able to capture either the electronic or the structural transition, but not both. As a result, researchers were forced to infer what the unseen component was doing, leading to the apparent conclusion that VO_2 experiences a step-like switch from insulator to metal. ï¿½We can now see both electronic and structur l changes directly, which occur faster than previously thought. Moreover, our new approa h has revealed an entire transition pathway. This means that attempts to control pha e transitions might be more complicated to implement, but also have many more potenti l outcomes. Instead of A or B, maybe we can drive materials into a whole alphabet of statesï? ½, shares Dr. Allan Johnson, IMDEA Nanoscience researcher and corresponding author of the st

The complete picture of VO_2 phase transition

Using their novel method, the team captured the VO? phase transition on its natural timescale. According to their observations, the material begins as an insulator, then passes through a ?bad metal' phase (just 10 femtoseconds after being excited with light), oscillates between insulating and semi-metallic states, and finally settles into a conventional metallic phase around 100 femtoseconds later. The study not only mapped these rapid electronic changes, but also demonstrated that they are closely connected to shifts in the material's atomic structure, where vanadium ions go from a twisted to a neutral position in an intricate process.

These insights were made possible by the use of ultrashort laser pulses-just 1 to 5 femtoseconds long-with an exceptionally broad spectrum. The broad spectral range was crucial to resolve all energy bands simultaneously, allowing researchers to build a complete picture of the transition.

One of the biggest challenges, the team noted, was interpreting the novel data. ï¿½There w s such a dramatic break from previous experiments that we had to develop entirely n w theoretical models to describe the transition at such short timescalesï¿½, explains Dr. Lin Zhang, ICFO researcher and co-author of the study. For this, the researchers from CFO Quantum Optics Theory group developed an efficient theoretical approach to the light-induced phase transitions of VO_2, which they had published a few months earlier in npj quantum materials. The theoretical method, which incorporates all the essential physical ingredients of VO_2, proved to be a powerful tool for explaining the experiment's complex dynamics.

Importantly, the fact that the proposed technique revealed such a rich transition pathway in a well-studied material like VO_2 suggests that something similar could occur in other quantum materials too, and that more hidden complexities might be uncovered in the near future.

Reference:

Brahms, C., Zhang, L., Shen, X. et al. Decoupled few-femtosecond phase transitions in vanadium dioxide. Nat Commun 16, 3714 (2025).
DOI: https://doi.org/10.1038/s41467-025-58895-z

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