Sub-cycle terahertz microscopy down to the atomic scale

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The possibility of accessing matter on both ultrasmall length scales and ultrafast time scales simultaneously has defined a new experimental frontier with the potential to significantly impact physics, chemistry, materials science, and biology. On the smallest length scales of stable matter, the motion of individual atoms, molecules, and electronic orbitals generally occurs on the femtosecond to picosecond time scale. This is also the time scale of low-energy elementary excitations in solids such as plasmons, phonons, and interlevel transitions in excitons.
In this talk, I will show how these diverse dynamics can be studied on their intrinsic length and time scales with techniques that combine terahertz technology with scanning probe microscopy. First, I will describe how ultrafast near-field microscopy has been employed to perform sub-cycle multi-terahertz spectroscopy on the surfaces of single nanoparticles [1] and resolve transient interface polaritons in van der Waals heterostructures [2]. Then, I will discuss an emerging new technique called lightwave-driven terahertz scanning tunneling microscopy (THz-STM) [3-6]. Here, strong THz fields at an STM tip apex quasi-statically modify the energy landscape of the tunnel junction as they oscillate, thereby generating femtosecond current pulses. We build on this concept, introducing state-selective lightwave-driven tunneling in the regime of single electrons [4]. We further unite THz-STM with cutting-edge single-molecule STM imaging [7], resolving 100 femtosecond snapshot images of the electron density within a single orbital of a single pentacene molecule [4]. Finally, we use femtosecond orbital imaging to resolve the ultrafast vibrations of the pentacene molecular frame in the time domain through a THz-driven quantum pump-probe experiment [4].

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