# Ultrafast dynamics of electrons, excitons and phonons in momentum space

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The dynamics of quasi-particles in non-equilibrium states of matter reveal the underlying microscopic coupling between electronic, spin and vibrational degrees of freedom. We aim for a quantum-state-resolved picture of coupling on the level of quasi-particle self-energies, which goes beyond established ensemble-average descriptions, and which requires ultrafast momentum-resolving techniques. The dynamics of electrons and excitons is measured with four-dimensional time- and angle-resolved photoelectron spectroscopy (trARPES), featuring a high-repetition rate XUV laser source [1] and momentum microscope detector. I will exemplify this experimental approach by discussing electron and exciton dynamics in the semiconducting transition metal dichalcogenide $WSe_2$ [2,3] and discuss its extension to nanoscale heterostructures. Our approach provides access to the transient distribution of hot carriers in the entire Brillouin zone of photo-excited semiconductors and allows the quantification of energy relaxation dynamics.

The complementary view of ultrafast phonon dynamics is obtained through femtosecond electron diffraction. The elastic and inelastic scattering signal reveals the temporal evolution of vibrational excitation of the lattice and momentum-resolved information of transient phonon populations [4].

In addition, to investigations in the weak-perturbation limit, intense ultrashort laser pulses can be employed to impulsively trigger photo-induced phase transitions. I will discuss the application of trARPES to atomic indium wires on a silicon substrate, a prototypical material system exhibiting a metal-insulator phase transition. Upon strong excitation inducing phase transitions, trARPES reveals the full transient electronic structure driving the structural transition along the reaction coordinate [4].

## References

1. M. Puppin et al., Rev. Sci. Inst. 90, 23104 (2019).

2. R. Bertoni et al., Phys Rev. Lett. 117, 277201 (2016).

3. D. Christiansen et al., Phys. Rev. B 100, 205401 (2019).

4. L. Waldecker et al., Phys. Rev. Lett. 119, 036803 (2017).

5. C.W. Nicholson et al., Science 362, 821 (2018); Phys. Rev. B 99, 155107 (2019).