Utilizing light-matter interaction to monitor and control excitations across internal interfaces

Low-dimensional quantum structures of compound semiconductors such as type-I quantum wells are the backbone of the established optoelectronic devices. Their fundamental properties have been intensely studied for more than half a century. The accompanying immense development in materials quality are indispensable for reliable long term device performance and true scalability, presumably the two prime advantages of semiconductor technology. More recently, heterostructures featuring type-II band offsets offer additional degrees of freedom in tailoring their optoelectronic response. From a fundamental standpoint, these type-II heterostructures offer the potential to investigate charge-transfer-like excitations. These developments have been accompanied by stringent development of microscopic theoretical description. The interplay of experimental and theoretical research has successfully fostered design and understanding of this class of quantum structures. Regardless, even decades old predictions remain under discussion as they have not been demonstrated experimentally.

This colloquium reviews the potential of light-matter interaction to monitor, clarity, and eventually control quasiparticle excitations in semiconductor quantum structures. The virtues and caveats of photon-based techniques are reviewed. Understanding the ultrafast dynamics of type-II heterostructures is crucial for the design and optimization of next-generation mid-infrared light sources. By tailoring the band offsets, it is possible to reduce the emission energies of active devices, potentially eliminating Auger losses. Furthermore, these structures serve as ideal model systems for investigating the structure and dynamics of excitations across internal interfaces.

Exemplary experimental observations of the nonlinear dynamics are presented using various techniques such as polarization resolved four wave mixing, optical-pump optical-probe, and optical-pump terahertz-probe spectroscopy. In type-II heterostructures, this holistic approach reveals, e.g., spectroscopic signatures consistent with biexciton states of charge-transfer excitons. For applications, type-II active devices combine the advantages of a spectrally broad, temperature stable efficient gain with the potential for electrical injection pumping. The intrinsic charge-carrier relaxation dynamics limit the feasible repetition rates beyond constraints of cavity design and heat removal. Here, we investigate the initial buildup of gain after optical excitation as well as its recovery after a stimulated emission process in the near infrared.