A complementary approach to the study of carrier dynamics in modern semiconductor structures

The lifetime of the carriers (electrons and holes) in semiconductors play a key role in the application of these materials in semiconductor devices such as light detectors, solar cells, transistors and light emitters, including lasers. Getting to know the so-called inherent lifetime of the carrier (i.e. the lifetime that would correspond to the situation in an ideal crystal) is not simple due to additional processes taking place in semiconductors such as the capture of carriers by non-radiative recombination centers (i.e. point defects such as vacancies, impurity atoms, atoms in interstitial positions), crystal surface states, dislocations or other imperfections in the crystal. While the mentioned processes lead to the shortening of the lifetime of the carriers, there are also processes that lead to the elongation of the life of the carriers, and one of them is the spatial separation of the carriers caused by the built-in electric field. As a result of this spatial separation, the carriers cannot recombine radiatively and therefore their lifetime is elongated.

The experimental study of the lifetime of carriers is based on the study of the dynamics of physical processes in which excess carriers participate. It comes down to the fact that the lifetime of the carrier is not measured directly. In the measurements of time-resolved microwave photoconductivity (TRMC), the dynamics of changes in photoconductivity caused by a short light pulse is investigated. Photoconductivity is proportional to the concentration of excess carriers and is probed with microwaves in TRMC measurements. Hence, it is assumed that the lifetime of the excess carriers describes the signal decay in TRMC. Time-resolved photoluminescence (TRPL) measures the dynamics of photoluminescence after the excitation of the semiconductor sample with a short laser pulse with photon energy larger than the band gap of the investigated semiconductor. In this way, a photoluminescence decay time is obtained, which depends on the time of radiative, non-radiative recombination and other processes, which do not lead to light emission (Auger processes and others). While in TRMC measurements one type of carriers is enough to obtain photoconductivity, in TRPL measurements two types of carriers are needed for the radial recombination to occur and the TRPL signal to be observed. This means that the carrier lifetime plays a key role in the dynamics of the processes responsible for generating the TRMC and TRPL signal, but the TRMC and TRPL dynamics need not be the same even when the lifetime of the carriers is the same. In addition to the carrier lifetime, the dynamics of TRMC and TRPL signals is determined by additional processes that can be very important in semiconductor devices and that are worth learning about.

Current designs of TRMC measurement systems allow measurements of lifetimes longer than ~ 10 ns, while in many semiconductors with the direct gap the carrier dynamics is much faster. Therefore, so far, the TRMC method has been used mainly to study the lifetime of carriers in semiconductors with the direct gap in which the lifetime of carriers is much longer (i.e., μs). In this type of materials, the lifetime of carriers is not investigated by the TRPL method due to the poor emission efficiency caused by the indirect gap. In perovskites, the decay times of photoluminescence are much longer and these materials have been studied by both the TRMC and TRPL methods, but so far such measurements have not been carried out under exactly the same excitation conditions, while it is known that different physical processes manifest and dominate under different excitation conditions.

Currently, in TRMC measurements, the photoluminescence signal is not measured and analyzed, which is understandable considering the fact that this method was developed to study semiconductors with an indirect gap that do not emit light. Improving the temporal resolution in TRMC measurements is now possible thanks to faster oscilloscopes, and therefore it is possible to study the carrier dynamics using the TRMC method in semiconductors with a direct gap. In addition, for materials with the direct gap that emit light, it is possible to measure TRPL as an additional phenomenon in TRMC measurements. Therefore, the aim of this project is to build a special research system for simultaneous TRMC and TRPL measurements and to carry out research on the dynamics of carriers for selected semiconductor materials for which we expect a high complementarity of these two methods, i.e. TRMC and TRPL

Since the experimental set-up developed within this project will be unique in the world scale, we will have opportunities to perform exceptional studies of carrier dynamics in many semiconductor materials. In this project we are going to focus on perovskites, van der Waals crystals, and hybrid structures containing these materials, which are currently the subject of intense research. We believe that using the combined TRMC and TRPL we will be able to understand much better the role of surface and defect states in carrier dynamics as well as the influence of separation/accumulation of carriers on their dynamics. The results obtained on various material systems will allow us to verify our hypothesis regarding the complementarity of both techniques, i.e. TRMC and TRPL. Moreover, the planned experiments will help to answer many current questions concerning the carrier dynamics in perovskites and van der Waals crystals, which are described in this proposal.