Excitons and plasmons in low-loss EELS of 2D monolayers and heterostructures

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Since the discovery of graphene, a huge number of new 2D materials have been discovered. In contrast to graphene, which is conducting, atomically thin layers of other materials can be semiconducting or insulating. Some also exhibit anisotropic properties [1]. Eventually, by stacking them to vertical 2D heterostructures, dielectric properties can even be tailored via the choice of the constituent monolayers, or the number of layers. With low-loss EELS in a monochromated low-voltage TEM, these dielectric properties can be obtained for a large energy range. Moreover, if the EELS signal is recorded for different scattering angles, the dispersions of different excitations such as plasmons and excitons can be studied.

In this work, we present low-loss EELS experiments with 2D transition metal dichalcogenides (TMDs) and graphene. In particular, we have investigated the energy-loss signal of WS_2 (see Fig. 1) and MoS_2 monolayers, as well as graphene and MoS_2 heterostructures. Our experiments have been performed at 80 kV in the SALVE III FEI Titan C_S/C_C-corrected SALVE (sub-Angstrom low-voltage electron microscopy) instrument [2, 3], as well as at 40 kV in the SALVE I Zeiss Libra 200 based prototype [4]. Due to monochromation, both microscopes have an energy resolution of 0.1 eV. Momentum-resolved EELS signals were obtained with a momentum resolution of up to 0.1 $Å^{-1}$. For monolayer WS_2 and MoS_2, we have investigated the influence of vacancies and extended defects on the peaks that are related to excitons, interband transitions and plasmons.

For the graphene and MoS_2 heterostructures, the interactions between excitations in different layers (MoS_2, graphene) were studied with simulations based on ab-initio calculations for different scattering angles. Long-range Coulomb interactions in heterostacks were introduced with efficient dielectric model calculations of different complexity [5]. In this context, the role of the interlayer distances for the low-loss spectra will be discussed. Furthermore, we want to point out the importance of the cleanliness of the 2D samples, and of the reduction of beam damage. To this end, we evaluate the prospects of a graphene encapsulation technique [6,7] for the damage-free investigation of more beam-sensitive 2D materials. [8]

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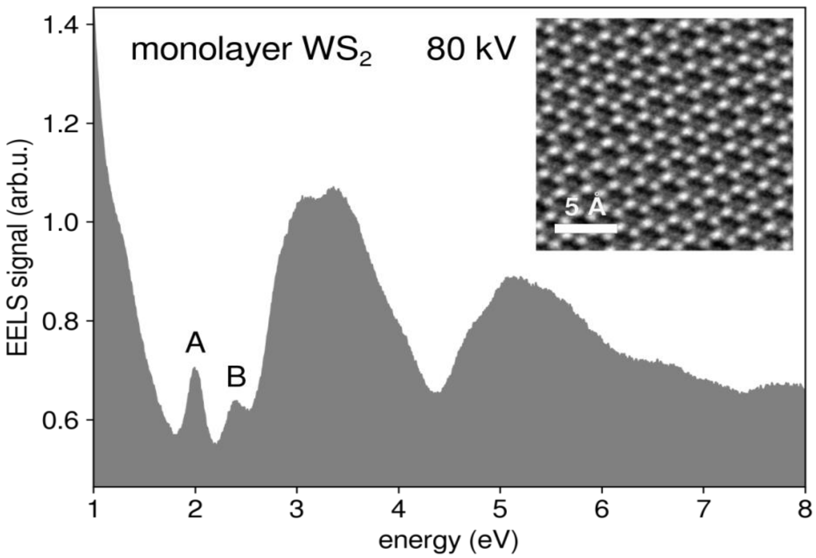

Fig. 1. Raw low-loss EELS signal of pristine monolayer WS_2, with A and B exciton peaks at 2.0 eV and 2.4 eV, respectively. The inset shows an unprocessed C_s/C_c-corrected HRTEM image of the monolayer.