Emission excitation spectroscopy in WS_2 monolayer encapsulated in hexagonal BN

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As the optical response of monolayers of semiconducting transition metal dichalcogenides is dominated by the emergence of tighly-bound excitons characterized by large oscillator strength, made them promising platform for studying two-dimensional physics.

Here, we report on emission excitation (EE) spectroscopy performed on high-quality monolayer WS_2 encapsulated hexagonal BN at T= 5 K. This method, which is analogous of the photoluminescence (PLE) and Raman scattering excitations (RSE), relies on tracing the emitted light when the detection energy of the outgoing photons is fixed and the laser energy is being swept.

Figure presents the false-colour map of the optical response set at emission related to the ground state of the neutral exciton (X^{1s}). As can be appreciated, there are several resonances, which appear with sweeping of excitation energy. Consequently, three energy regions of excitation can be distinguished. In the lowest energy one (<30 meV), a large growth of the X^{1s} intensity with decreasing of excitation energy is visible, which is due to an efficient creation of excitons characterize by high angular momentum. The middle range (>30 meV and < 110 meV) is dominated by several nicely pronounced narrow lines, *e.g.* 2ZA, E', and A'$_1$, following the laser excitation energy which points out to Raman scattering as their origin. These peaks give rise to the an extremely rich RSE spectrum. We found that the Raman resonance condition is reached when the energy difference between the excitation and X^{1s} energies is equal to the phonon energy, which is known as out-going resonance conditions. Moreover, the resonance profiles of observed phonon modes reflect the X^{1s} lineshape with width of about 5 meV. Two broad resonances apparent at the highest excitation energies (>110 meV) are tentatively attributed to the first excited states of X^{1s}, *i.e.* X^{2p} and X^{2s}, which form a PLE spectrum.

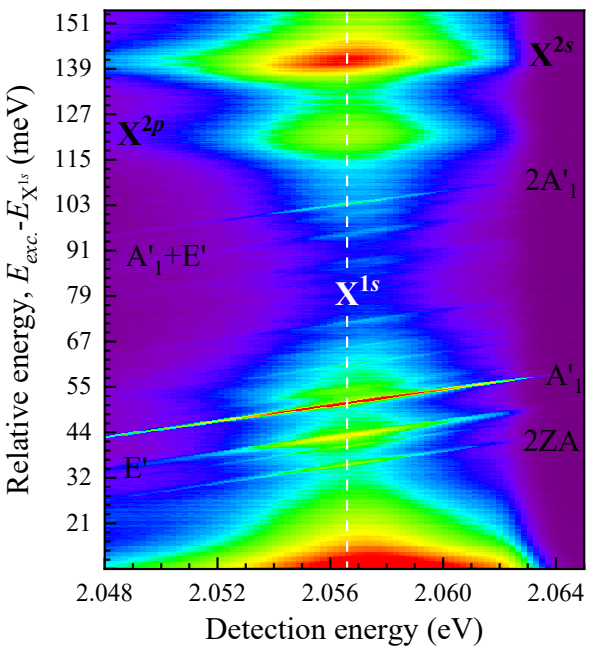

Figure Optical response of monolayer WS_2 at T=5 K plotted as a function of relative excitation energy.

We demonstrate that emitted light of monolayer WS_2 at the specific range of excitation energy is combine of both Raman scattering and photoluminescence signal, which give us important information of both excitons-phonon interaction and a ladder of excitonic states.