**Low-temperature photocarrier dynamics in single-layer $MoS_2$ flakes**

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## Abstract

The dichalcogenide $MoS_2$, which is an indirect-gap semiconductor in its bulk form, was recently shown to become an efficient emitter of photoluminescence [1,2] as it is thinned to a single layer, indicating a transition to a direct-gap semiconductor due to confinement effects. The material is a layered structure of weakly coupled, covalently bonded two-dimensional sheets, and it can be prepared, just as graphene, using chemical or mechanical exfoliation techniques.
Here, we present temperature-dependent and time-resolved photoluminescence (PL) studies [3] of single-layer $MoS_2$ flakes, some of which have been covered with thin dielectric layers ($HfO_2$ or $Al_2O_3$) using atomic layer deposition (ALD). The flakes are prepared from bulk $MoS_2$ by transparent tape liftoff. For initial characterization, optical, atomic-force and Raman microscopy are used (Fig.1). We observe that the PL peak position of individual single-layer $MoS_2$ flakes fluctuates by about 25 meV at room temperature. Mild annealing at 150°C in vacuum leads to a homogenization of the PL peak position. For as-prepared flakes, we clearly see two PL peaks at low temperatures, which we may assign to bound and free exciton transitions (Fig. 2a). Oxide-covered flakes only show the free exciton peak, indicating that bound excitons form due to adsorbates at the flake surface (Fig. 2b). [4]. Temperature-dependent PL measurements indicate that the oxide-covered flakes are strained due to different thermal expansion coefficients of $MoS_2$ and the oxides. This observation also indicates that the flakes strongly adhere to the oxide layers. Strain strongly influences the band structure in single-layer dichalcogenides and may even cause a metal-insulator-transition [5]. In time-resolved PL measurements using highly nonresonant, pulsed excitation, we observe very fast photocarrier recombination on the few-ps timescale at low temperatures, with increasing photocarrier lifetimes at higher temperatures due to increased exciton-phonon scattering (Fig. 2c). Excitons which are scattered out of the light cone by phonons first have to relax their momentum before they are able to recombine radiatively.
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## References

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## Figures

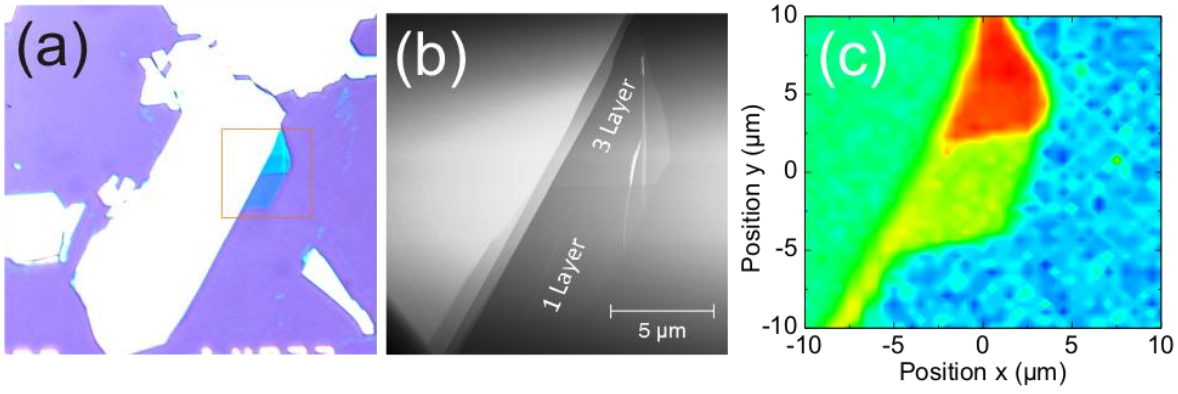


**Fig. 1**: (a) Optical micrograph of a thin $MoS_2$ flake. (b) AFM scan of area marked in (a) by orange square. (c) False color plot of the intensity of the $MoS_2$ $E^1_{2g}$ Raman mode.

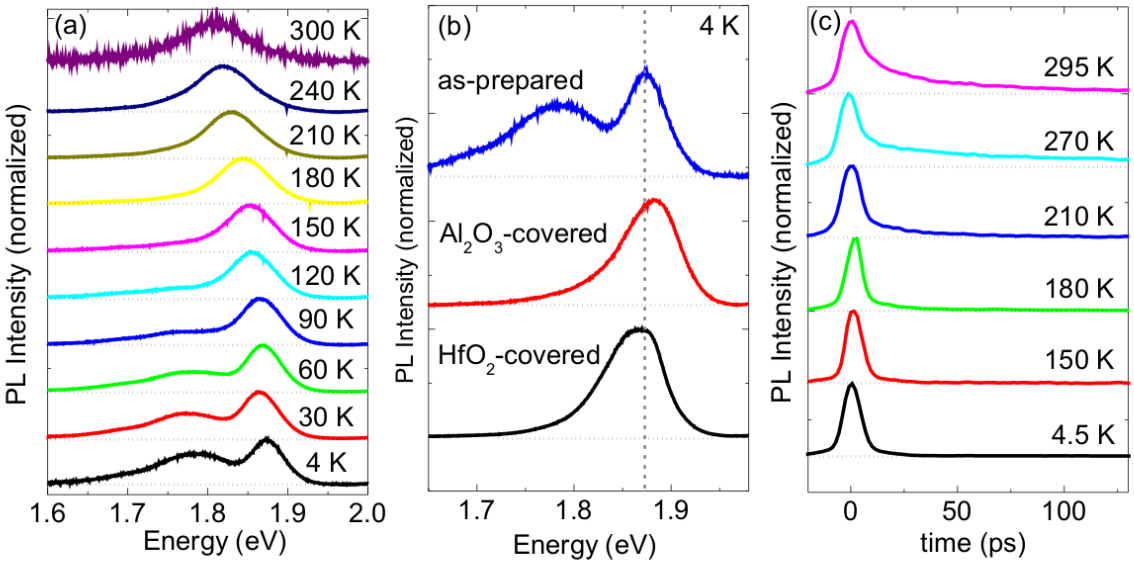


**Fig. 2**: (a) Temperature-dependent PL spectra of single-layer $MoS_2$. (b) PL spectra of bare and oxide-covered single-layer $MoS_2$ measured at low temperatures. (c) Temperature-dependent Time-resolved PL traces of single-layer $MoS_2$.