Control of Radiation Damage in MoS$_2$ by Graphene Encapsulation

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Supporting Information

**EELS data processing:** SI de-noised using Principal Component Analysis (13 components), S L$_{2,3}$ edge integrated over a 55eV window immediately above the edge onset at 165eV. Mo M$_{4,5}$ integrated over a 25eV window placed 20eV after the edge onset to avoid S L$_1$ edge and avoid possible volcano structures.$^1$ Note that the Mo map is not considered to be fully quantitative due to background subtraction difficulties and is therefore only shown as an indication. S and Mo maps display the full intensity range, but the composite image contrast is adjusted to improve lattice visibility.

**Image simulations:** Multislice image simulations of a free-standing MoS$_2$ sheet and of the graphene/MoS$_2$/graphene stack were carried out using the QSTEM software suite.$^2$ The model of the encapsulated structure was constructed by stacking single layers of graphene and MoS$_2$, separated in the z-direction by 1.55 Å (corresponding to the approximate distance along z between the Mo and S planes): a 3D representation of this (rather crude) model was used to generate the Table of Contents graphic. For simplicity, no rotation was applied between the layers. Thermal diffuse scattering was taken into account through a frozen phonon approximation: a total of 15 different frozen phonons were used. Experimentally measured
beam convergence (31 mrad), detector inner and outer radii (79 to 195 mrad) and aberration coefficients (for simplicity, only $C_5=5 \mu m$, $C_5=-8mm$ and $C_c=1.1mm$ were considered) were used as input for the simulations. Probe size effects were included by convoluting the simulated images with a 0.8 Å (FWHM) Gaussian distribution.

**Movie_1** (256x256 pixels) was recorded with 5.1 μs dwell time and showing 5frame/sec of total 150 frame (MoS$_2$).

**Movie_2** (512x512 pixels) was recorded with 5.1 μs dwell time and showing 5frame/sec of total 160 frame (graphene/MoS$_2$).

**Movie_3** (256x256 pixels) was recorded with 1.3 μs dwell time and showing 10frame/sec of total 385 frame (graphene/MoS$_2$/graphene).

Figure S1. Survey HAADF image (raw data) and the resulting chemical maps (EELS maps) of pristine single layer MoS$_2$. The maps were acquired over the blue-framed rectangular area indicated on the survey image.
Figure S2. Atomic resolution HAADF image taken after movie_2 (the image is in fact the last frame of the movie). a) shows the image as presented in fig. 2e of the main manuscript (raw data). b) The image contrast is adjusted to make the graphene lattice visible under the perforation in the MoS$_2$ sheet, confirming that is undamaged.

Figure S3. Survey HAADF image (raw data) and the resulting chemical maps (EELS maps) of the graphene/MoS$_2$ stack. The maps were acquired over the blue-framed rectangular area indicated on the survey image.
Figure S4. Atomic resolution HAADF image of an area where the MoS$_2$ terminates, leaving only exposed a bare suspended single-layer graphene sheet. a) Unprocessed image in which the MoS$_2$ lattice is clearly visible in the upper half of the image. b) Same image as (a) but with the brightness and contrast adjusted to reveal the graphene lattice, clearly observed in the bottom half of the image. c) shows the Fourier Transform of (a), with both graphene and MoS$_2$ reflections visible. d) Fourier Transform of the red-dashed rectangular marked in (a) with only graphene spots visible. e) Fourier filtered version of (a) obtained by selecting the MoS$_2$ reflections only (and cutting out the graphene reflections as illustrated in (g)). These images illustrate well the fact that the supporting graphene layer only has a minor effect on the contrast and the image quality in the MoS$_2$ flake. f) Fourier filtered image of (a) obtained by selecting only the graphene reflections as illustrated in (h): the graphene lattice is clearly visible on the bottom half of the image, but not as apparent in the upper section, even though simultaneously acquired bright field STEM images show that graphene is indeed present throughout the whole frame. This confirms that the presence of the carbon lattice only marginally affects the visibility of MoS$_2$: individual carbon atoms are not resolved in these images. We note that surface contamination (hydrocarbons residue from the transfer process) obscures most of the area under the MoS$_2$ sheet in this case and may contribute to the poor visibility of the graphene layer.
Figure S5. Image simulations of the MoS$_2$ and of the encapsulated structure (graphene/MoS$_2$/graphene) carried out using the QSTEM software suite. Both images are on the same color and intensity scale, illustrating the loss of contrast due to the presence of the encapsulating layers. Note however that the graphene lattice is not visible in the simulated image for the encapsulated structure, as is observed experimentally.

Figure S6. Survey HAADF image (raw data) and the resulting chemical maps (EELS maps) of the pristine graphene/MoS$_2$/graphene encapsulated structure. The maps were acquired over the blue-framed rectangular area indicated on the survey image. Note the possible S single vacancies in the S maps, seen from lower S intensity in at least 2 positions, not obvious in the simultaneous HAADF image.

References
