Quasi-2D crystalline materials are widely investigated to explore their optical, electronic and mechanical properties. The most prominent examples in this class of materials are graphene, hBN, and recently dichalcogenites, e.g. MoS$_2$. The third dimension of those crystals may not be neglected since freestanding membranes are thermodynamically forced to form intrinsic ripples. Moreover, the resulting topography of such materials is expected to have a severe influence on their properties. For example, strain, which can alter the band structure, is caused by any change of the surface inclination. In graphene corrugations have already been confirmed by Meyer et al. applying electron diffraction [1].

Inspired by that study we developed a method to determine the topography of freestanding membranes by diffraction-contrast TEM imaging. The procedure is based on dark field (DF) tilt series using at least two independent \( g \)-vectors oriented perpendicular to the respective tilt axis. In those DF images, the measured intensity directly depends on the local excitation condition and thus on the local inclination of the membrane. By tilting, the reciprocal lattice rod (relrod) is scanned simultaneously in each sub-region of the DF images. To determine the inclination of each sub-region with respect to the specific \( g \)-vector, the maximum of the tilt-angle dependent intensity distribution is fitted. This is done for two different tilt series and the obtained data are used to calculate the absolute inclination of each sub-region and thus to determine the membrane topography.

We applied the procedure to freestanding membranes from high-quality epitaxial graphene on SiC [2]. Fig. 2a) depicts a representative \{11-20\} DFTEM image of such a few-layer graphene membrane. The local mean image intensity represents the number of graphene layers as proven by rocking curves. The sharp dark lines in the DF image are due to basal-plane partial dislocations, which have an additional impact on the local topography [3]. To demonstrate the strongly different intensity distributions along different directions Fig. 2e)-f) show exemplary DF images at 0 tilt for 3 independent \{11-20\} directions. It can be recognized that, while the wavy topography leads to strong, almost parallel contrast variations in the (11-20) and (1-210) images, the (2-1-10) DF image (with \( g \) perpendicular to the wave-direction) is less influenced.

While in the used example the basal-plane partial dislocations have a severe influence on the topography of the material, it will be shown that even the choice of the TEM support has a strong impact on the topography of defect-free membranes.

Acknowledgement: We acknowledge financial support by the Cluster of Excellence: Engineering of Advanced Materials and SFB 953: Synthetic Carbon Allotropes.
Fig. 1: a) Model of inclined membrane: Inclinations non-parallel to the used g-vector show intensity variations as indicated by the dark and light gray areas, b) Ewald sphere construction, c), d) enlargement for almost flat and strongly inclined membrane area.

Fig. 2: a) Graphene membrane with 2-, 3- and 4-layer areas (scale bar 500 nm), b)-d) rocking curves extracted from the areas indicated (2, 3, 4 layers), e)-f) 3-layer graphene DF images obtained with the 3 indicated g-vectors, dotted line shows tilt axis orthogonal to the reflection used for imaging.