Defect-engineering of 2D materials with ion and electron beams

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It is known since decades, that electron irradiation leads to damage in materials during imaging in (scanning) transmission electron microscopy. In materials prone to ionization or electronic excitations this is known to be largely due to inelastic electron scattering, whereas in conductive materials the main damage mechanism is knock-on damage caused by elastic electron scattering. However, it only became possible recently with the advent of aberration corrected microscopes and 2D materials to quantify the damage in detail. It was confirmed, that in graphene which is an excellent conductor, the observed atomic scale damage could indeed be explained via simple knock-on events [1]. In the mean while it also became obvious that the residual vacuum in the microscope column can in some cases play an important role in the damage creation. For graphene, this has been shown to only play a role at point defects and edges [2], whereas for oxygen sensitive 2D materials, such as MoTe2, it also influences areas with no defects [3]. In contrast to graphene, in semiconducting 2D materials such as MoS2 (for which the residual vacuum does not play a significant role [3]) it has recently been proposed [4] that the atomic-scale process underlying electron irradiation-induced damage arises from a combination of inelastic and elastic scattering, where the same electron first locally excites the electronic structure and at the same time scatters elastically from a nucleus in the material causing its displacement. It appears that this process can alternatively be explained either through impact ionization or direct valence excitation [5], but additional experimental data and further developed theoretical models are sorely needed to provide the final explanation. Similar to electron irradiation, also ion irradiation can be used to tailor the atomic structure of materials. In the simplest case, low energy ions displace atoms from the target material leaving behind vacancies [6]. In this contribution, we will show how this allows defect-engineering of graphene and hBN, but also heteroatom implantation via a two-step process [7]. Additionally, we show that low-energy ion irradiation of graphene structures beyond the monolayer can be used to trap noble gas atoms inside the van der Waals gap between individual layers [8]. The noble gas atoms form small 2D crystallites due to the pressure exerted by the attractive inter-layer interaction. This system allows for the first time direct observation of the structure and growth dynamics in 2D noble gas crystals through scanning transmission electron microscopy, and in addition to fundamental science of van der Waals structures may also provide important insights for statistical physics research.

References

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