Fabrication of well-ordered and defect-free two-dimensional (2D) structures on the nanoscale is of technological importance in energy storage and electronic devices [1]. The biologically-inspired processes, in which the biological entities (e.g. phages) serve as 2D scaffolds for the directed synthesis of a range of inorganic nanostructures, are essential for designing the next-generation multicomponent materials [2]. In order to induce in-situ growth of uniform and homogenous inorganic nanostructures, bio-assisted synthesis methods are utilized as promising tools to attain smooth organic-inorganic hierarchical layers. To this end, not only preparation of a densely-packed monolayer of biological entities onto specific surfaces is inevitable, but also achieving a directionally ordered pattern of the biological entities, extending in a long length range is crucial to enhance the functional properties of the final product. It has been reported that the surface chemistry, roughness and the state of hydrophobicity play important role in the surface protein adsorption and their further assembly [3].

In this study, filamentous wild-type (WT) M13 bacteriophages were deposited from a viral solution (< 5 mg/ml) on amorphous carbon (a-C) and silicon oxide (SiO\textsubscript{x}) surfaces. Using scanning electron microscopy (SEM) and transmission electron microscopy (TEM), we show that the a-C surface induces the assembly of M13 phages into parallel arrays. Figure 1 shows a bright-field TEM (BF-TEM) image of disordered phages immobilized on the SiO\textsubscript{x} surface. The trend of the system was towards the formation of an isotropic phase. However, viral particles show a high degree of alignment along a common axis on a-C surface as per nematic liquid crystalline model (see Figure 2). The M13 phage particles were found to have a high affinity for incorporation into the closely-ordered pattern onto a-C. Interestingly, the aforementioned architecture can be obtained by applying phage solution on the surface without employing nanoparticle assembly methods such as dip coating or convective assembly. Our strategy is to facilitate the immobilization process in a highly ordered manner, and to attain a fully covered surface with densely-packed and highly-oriented M13 phage viral particles in a long-range basis. Such closely-ordered pattern can further function as templates to nucleate highly uniform and smooth inorganic layers.

References

Acknowledgement: Financial support by the DFG for funding SPP 1569 is gratefully acknowledged. The research leading to these results has received funding from the European Union Seventh Framework Programme [FP7/2007-2013] under grant agreement n°312483 (ESTEEM2).
Fig. 1: BF-TEM image of randomly distributed WT M13 phages immobilized on a SiO$_x$ membrane from a droplet of M13 viral solution, depicting a highly disordered and web-like structure. The inset shows the 2D Fourier transform (FT) image of the corresponding BF-TEM image.

Fig. 2: BF-TEM image of WT M13 phages closely-packed and oriented on a-C support film from a droplet of M13 viral solution, showing the 2D alignment along a common direction. The inset shows the 2D FT image of the corresponding BF-TEM image.