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Imaging of Quantum Materials

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A fascinating class of quantum materials is atomically layered materials such as graphene or hexagonal boron nitride (h-BN). The properties of such materials differ strongly from those of their three-dimensional bulk state. Depending on the composition, quantum materials may act as conductors, insulators, semiconductors or even as superconductors. Combinations of multiple quantum materials are of high interest to explore new phenomena and to build the foundation for future electronic devices at the nanometer scale. We report on the imaging and characterization of several unique quantum materials systems, reaching from defect formation in graphene to the characterization of hybrid quantum materials. We use a C_s corrected Zeiss Libra TEM to investigate chemical vapor deposition (CVD) graphene with added copper and mercury defects. With TEM we examine the positioning of the Hg and Co atoms on the graphene lattice. At the same time, we observe the effect of the copper and mercury on the pi electrons in graphene with Raman spectroscopy. Furthermore, we examine graphene based hybrid structures, such as graphene oxide embedded in a vanadium pentoxide nanofiber matrix (Fig. 1). The graphene sheets and the nanofibers have approximately the same thickness, leading to a material with enhanced mechanical performance in comparison to pure vanadium pentoxide and pure graphene oxide sheets.

We also investigate quantum materials with superconducting properties, such as iron selenide (FeSe). As a bulk crystal, the superconducting critical temperature (T_c) of FeSe is a mere 8 K. However, recent reports showed that single-layer FeSe films grown on strontium titanate ($SrTiO_3$) may exhibit superconductivity at temperatures above 100 K [1, 2]. We combine STM and TEM measurements to investigate single unit cell FeSe grown by in situ molecular beam epitaxy on $SrTiO_3$. TEM is used to characterize the detailed structure of the FeSe and underlying SrTiO3 interface, while STM is used to probe the electronic states, both below and above the Fermi level.
Niobium-nitride (NbN) on top of graphene is a hybrid quantum material that is of great interest for its controllable superconductivity. In thick films, which essentially behave like a bulk material, this hetero structure is well characterized [3] and it has been shown that the charge density in the graphene can be controlled with a gate electrode, allowing the tuning of the superconducting behavior. In the present work we concentrate on the fabrication and characterization of a low dimensional version of a NbN-graphene hetero structure (Fig. 2), where the NbN has a thickness of only a few nanometers.

We have performed high-resolution electron microscopy in combination with STM and Raman spectroscopy, to investigate quantum materials. This combination proved to be an excellent tool to understand the astonishing mechanical and electronic properties.

References:

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[4] This work was supported by the STC Center for Integrated Quantum Materials, NSF Grant No. DMR-1231319

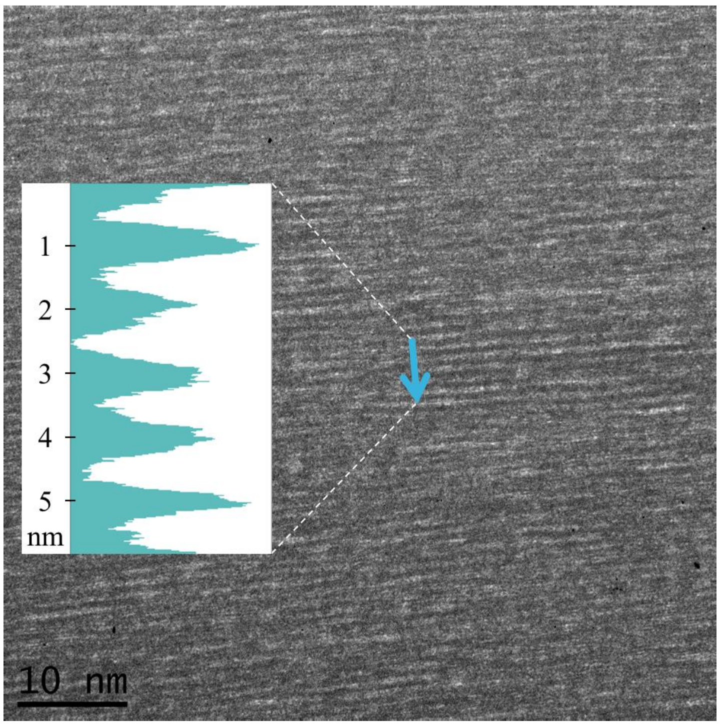

Figure 1. The image shows the structure of a free-standing thin-film composed of vanadium pentoxide nanofibers and graphene oxide nanosheets. Fibers and sheets both have an average thickness of 1 nm and oxygen-containing functional groups which promote the interaction between both components, leading to a material with enhanced mechanical performance in comparison to pure vanadium pentoxide and pure graphene oxide sheets.

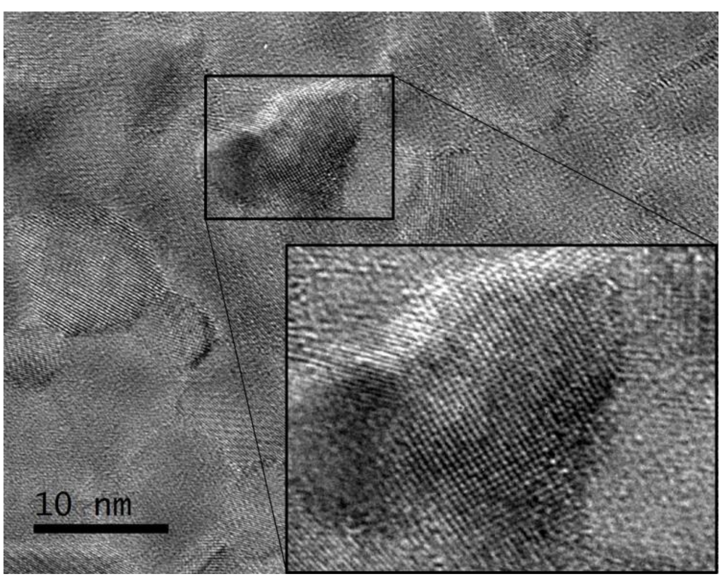

Figure 2. Niobium nitride (NbN) layer on CVD graphene. During the growth process, crystalline islands are formed, which merge to a continuous film.