Visualization of unoccupied states in the electronic structure of freestanding graphene by means of low-energy electron point source microscopy

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Abstract

We report the measurement of band signatures in the higher lying regime of unoccupied states in the electronic band structure of freestanding graphene. The electronic structure of solids is of great importance in condensed matter physics and the occupied states below the Fermi level are readily characterized experimentally, for example with angle resolved photoemission spectroscopy [1]. The higher lying unoccupied states however are experimentally much more difficult to measure [2].
The hereby newly introduced technique is based on low-energy electron point source microscopy (LEEPS) [3] and makes use of the energy and in-plane momentum dependence of the electron transmission through a freestanding graphene sheet. The method presented here allows probing the unoccupied states from a nanometer sized probing area at constant electron energy and a large range of $\boldsymbol{k}_{\parallel}$ in 2D in a single shot.

The LEEPS microscope setup consists of a coherent electron point source emitting a divergent beam of low-energy electrons towards the sample placed in a distance of typically a few tens of nanometers behind. The electron beam interacts with the sample and is afterwards captured at a macroscopic distance with a 2D detector unit based on a microchannel plate and a phosphor screen. Here we present LEEPS measurements recorded with extraordinarily small electron energies (18–30 eV) of single layer graphene prepared freestanding over holes in a silicon nitride membrane.

In the experiments we find an angular dependence of the electron transmission through the graphene sheet which we associate with unoccupied states in its electronic band structure. In a single LEEPS image the sample is probed with electrons of constant energy for a wide range of in-plane momentum components, which are determined from the electron incident angles. In a simple picture, the probability for an electron to be absorbed is high if its energy and in-plane momentum coincide with a state in an unoccupied band of the sample and consequently a reduced transmission intensity is measured. A high transmission is recorded if no corresponding free states are present in the sample.

The figure shows background corrected transmission images of freestanding graphene recorded at various electron energies in (a)-(f). The energies are relative to the Fermi level and the scale bar amounts to 0.3 $Å^{-1}$. Every image corresponds to a single shot LEEPS measurement and displays the 2D in-plane momentum dependence of the transmission. The direction to the high symmetry points M and K of the Brillouin zone are indicated in (e). The dark regions are associated with unoccupied states in the band structure, the most prominent band signatures form a dark hexagonal pattern in the $\boldsymbol{k}_{\parallel}$-space. In (g) a $E(k_{\parallel})$ plot in M and K direction extracted from a measurement series with electron energies from 30eV to 18eV in 1eV steps is shown.

References

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