Contactless Probing of Local Potential and Band Structure in Two-dimensional Materials by Low-energy Electron Microscopy

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Low-energy electron microscopy (LEEM) is a powerful surface science tool for investigating samples in real and reciprocal space via low-energy electron diffraction (LEED) and angle-resolved photoelectron spectroscopy (ARPES)(*1*, *2*). LEEM is particularly suited for graphene and other two-dimensional materials due to its supreme surface sensitivity. So far, LEEM has mainly been used for structural analysis, while information on electrical properties like conductance was not obtained. Here we present two novel LEEM-based techniques that fill this gap by measuring local band structure and local electrical potential.

In LEEM, spectroscopic information about the sample can be obtained by measuring LEEM-IV(*3*), i.e., the energy dependence of the reflected electron intensity. In layered van der Waals materials, for example, pronounced oscillations of the intensity are observed. The number of minima can be related to the number of atomic layers at every point of the image. This is routinely used to count the number of graphene layers unambiguously(*4*, *5*). In addition,we find systematic changes in the shape of the IV-curves depending on the tilt angle between electron beam and crystallographic axes of graphene. This angle determines the in-plane momentum. These changes are determinedby the dispersion relation of the material. The band structure of samples can thus be determined from LEEM movies directly, i.e., without any further calculation or assumptions. Moreover, this novel technique can be applied to real-space movies, and on areas as small as a couple of square nanometers. This allows us to accurately specify the region where the band structure is measured on non-uniform samples as, for example, exfoliated graphite flakes (Fig. 1).

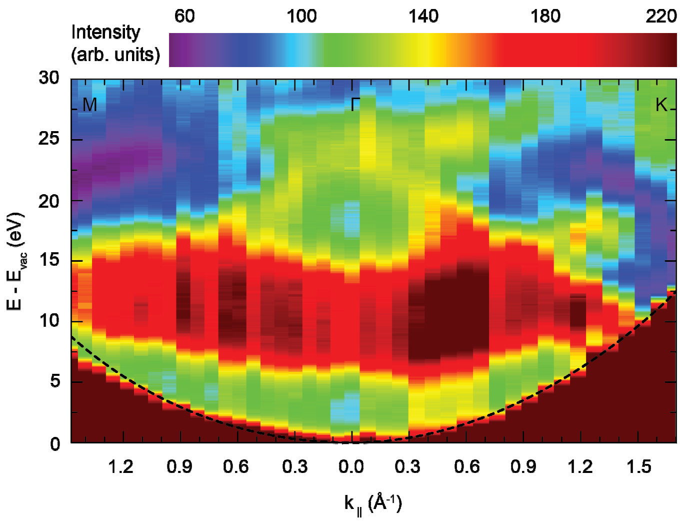

Figure 1: Two-dimensional false-color representation of IV-curves for different in-plane momenta for a measurement on an exfoliated graphite flake. It reflects the band structure, where high reflected intensity (red) corresponds to band gaps and low intensity (blue) to electronic states in the solid that couple to the incoming/reflected plane wave electron beams.

In addition, we studied graphene devices with a voltage applied across them. We find that the IV-curves in that setup are shifted according to the local electrical potential. By studying this shift, we can therefore determine a high-resolution map of the local potential (cf. Fig. 2). We find that steps in the silicon carbide substrate do not disturb charge transport significantly, while changes in graphene layer thickness act as strong scatterers. This can be related to wave-function mismatch between monolayer and thicker layers(*6*).

Both novel methods are fast, contact-less and offer high lateral resolution due to the use of real-space LEEM movies. Therefore, they are perfectly suited to study novel two-dimensional materials that are frequently not homogeneous over large areas.

References

1. R. M. Tromp et al., A new aberration-corrected, energy-filtered LEEM/PEEM instrument. I. Principles and design. Ultramicroscopy. 110, 852–861 (2010).
2. R. M. Tromp, J. B. Hannon, W. Wan, A. Berghaus, O. Schaff, A new aberration-corrected, energy-filtered LEEM/PEEM instrument II. Operation and results. Ultramicroscopy. 127, 25–39 (2013).
3. P. W. Sutter, J.-I. Flege, E. A. Sutter, Epitaxial graphene on ruthenium. Nat. Mater. 7, 406–11 (2008).
4. H. Hibino et al., Microscopic thickness determination of thin graphite films formed on SiC from quantized oscillation in reflectivity of low-energy electrons. Phys. Rev. B. 77, 075413 (2008).
5. N. Srivastava et al., Low-energy electron reflectivity of graphene on copper and other substrates. Phys. Rev. B. 87, 245414 (2013).
6. S.-H. Ji et al., Atomic-scale transport in epitaxial graphene. Nat. Mater. 11, 114–119 (2012).

[1] H.G. Hansma et al., Microsc. Microanal. 5 (Suppl. 2) (2002) 1012.
[2] M.A. Rodrigues, Thin Soli Films, 6 (2000) 1192.
[3] J.I. Goldstein et al., Scanning Electron Microscopy and X-ray Microanalysis, Plenum, New York, 1992.

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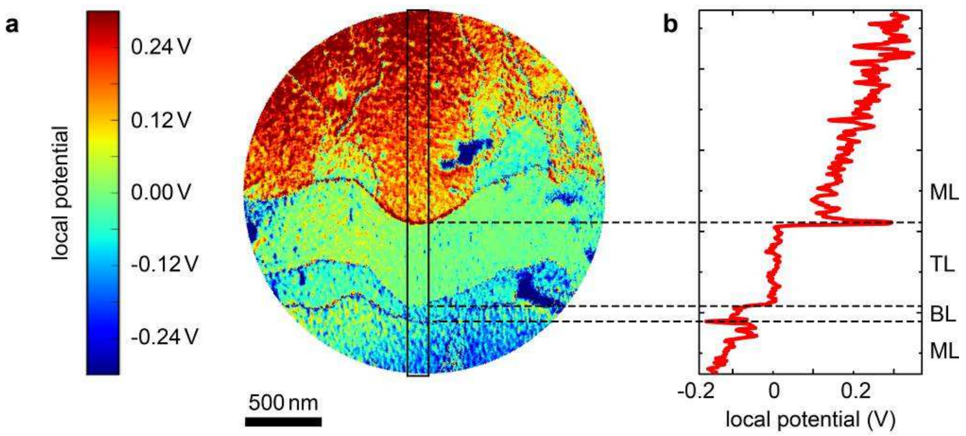

Figure 2: (a) A potential map derived from shifts of local IV-curves. Current flows from top to bottom. (b) The profile [rectangle in (a)] reveals a different resistivity for monolayer (ML), bilayer (BL) and triple layer (TL) graphene and indicates an additional voltage drop at the steps between areas of different layer thickness.