Conductance mapping of graphene using dual-probe STM

Mikkel Settnes[*], Stephen R. Power, Dirch H. Petersen, and Antti-Pekka Jauho

Center for Nanostructured Graphene (CNG), Department of Micro- and Nanotechnology Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark

We demonstrate anisotropic conductance in graphene using a dual-probe Scanning Tunnelling Microscopy (STM) setup as sketched on Fig. 1. This setup allows us to calculate the local electrical conductance at a designated position in the sample. Electrons injected at one probe are propagating through the sample and collected at another probe. The transmission between different point yields more information than what can be extracted from a standard STM setup measuring topography or local density of states.

Using one probe in scanning mode while fixing the other, we are able to compute real space conductance maps showing anisotropic behaviour depending on the underlying crystal direction (Fig. 2). The features of the dual-probe transmission are explained very transparently using analytic expressions for graphene Green's functions [2].

Fixing both probes and using a gate to vary the Fermi energy, the energy dependent conductance clearly shows different fingerprints depending on armchair and zigzag directions (Fig. 3). Multi-probe spectroscopy also appears to be a promising tool for characterizing individual modifications of the graphene sample such as perforations or grain boundaries.

Recent experimental progress in multiple STM probe techniques enables positioning of two STM tips as close as 50-100 nm [1], a length scale within the inelastic mean free path of graphene. Thus we consider ballistic transport and quantum interference effects remain. We investigate such interference effects around impurities (Fig. 4) and crystalline edges [3]. We show that impurities and their positions relative to the probes can be distinguished by their scattering signature in real and Fourier space. This is seen in analogy to optical diffraction.

The theory developed treats point probes on an *infinite* sheet of graphene, which is in contrast to the conventional Landauer geometry containing semi-infinite contacts connected to a *finite* sample. This necessitates a reformulation of the conventional recursive Green's function method. We utilize contour integration techniques to evaluate the Green's function for infinite pristine graphene [2]. The approach is valid for a wider range of energies, thus going beyond the linear regime.

Defects are added using a Dyson equation approach, which keeps the computational size of the problem proportional to the number of defects and contact sites, rather than the sample size, allowing for an easy investigation of long range features.

References

[1] An-Ping Li, Kendal W. Clark, X.-G. Zhang, and Arthur P. Baddorf. *Advanced Functional Materials*, 23(20):2509–2524, May 2013.

[2] S. R. Power and M. S. Ferreira. *Physical Review B*, 83(15):155432, April 2011.

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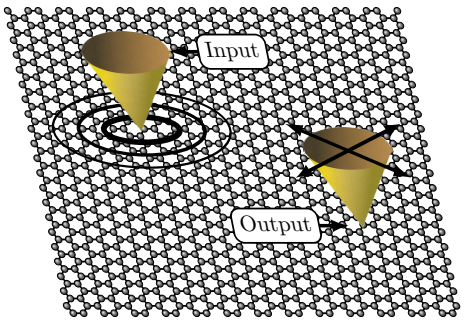

Figure 1: Schematic of the dual-probe STM setup.

[*]mikse@nanotech.dtu.dk

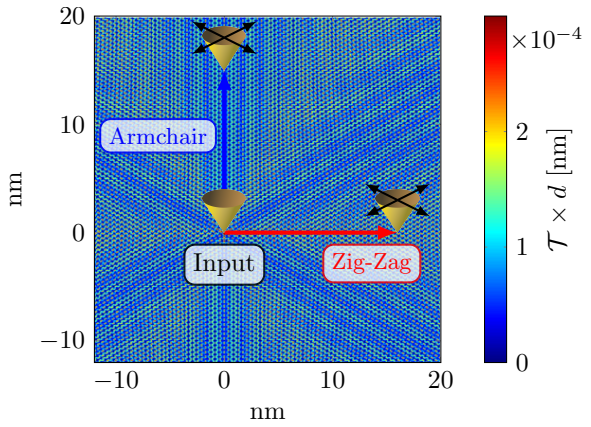

Figure 2: Scanning the output tip over the sample gives the real space conductance map shown with distinct characteristic of the armchair (constant) and zigzag (oscillatory) directions.

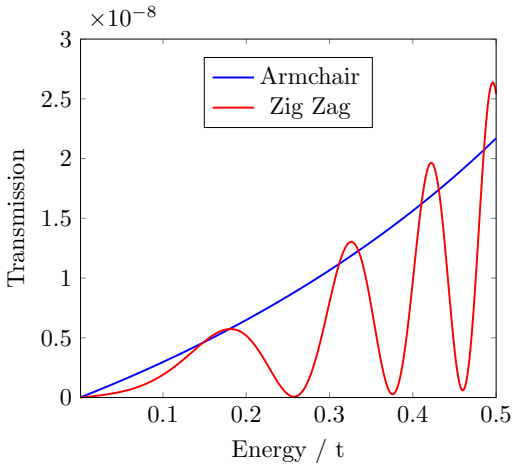

Figure 3: Spectroscopy of two probes separated in the armchair and zigzag direction, respectively. The probe separation is $\sim$ 50 nm. A clear difference is observed between the armchair and zigzag directions. The armchair shows the usual linear increase of the density of states characteristic of graphene. However, the zigzag direction exhibits oscillations due to Fermi surface asymmetry.

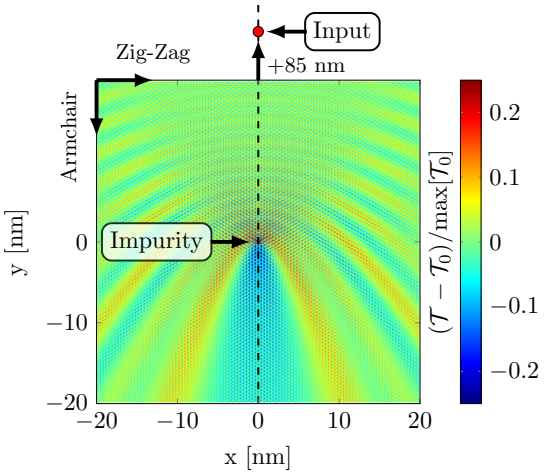

Figure 4: Real space map of conductance between input (outside the scan area) and scanning probe, around an impurity located at the origin. The figure shows the relative change compared to the pristine case ($\mathcal{T}_0$). The separation between the impurity and the fixed probe is in the armchair direction. A shadowing effect is clearly visible in the blue regions with low transmission behind the impurity.