In Situ Manipulation of Topological Defects in Bilayer Graphene

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Topological Defects known as dislocations have a tremendous impact on the properties of virtually any crystalline material. Since their discovery in the 1930s[1-3] a lot of effort was put into controlling the amount and type of dislocations in materials. For Semiconductors these defects often lead to charge carrier recombination[4], whereas in Metals they can lead to hardening[5]. For 2D Materials the effect of defects becomes even more severe, necessitating a deeper understanding of their behavior. For bilayer graphene, the thinnest material to host in-plane dislocations, interesting phenomena such as valley transport[6] and plasmon reflection[7] at dislocations were shown, however controlling the structure of dislocations has remained elusive so far.

In this work we present a novel approach to directly manipulate individual dislocations *in situ* using transmission mode Scanning Electron Microscopy (tSEM). A fine tip on a micromanipulator is used to move the dislocations in bilayer graphene like a carpet fold (see Figure 1 a). This is enabled by the spacious environment combined with the high spatial resolution and ability to image crystallographic information in transmission mode provided by modern SEMs (see Figure 1 b for the in situ setup).

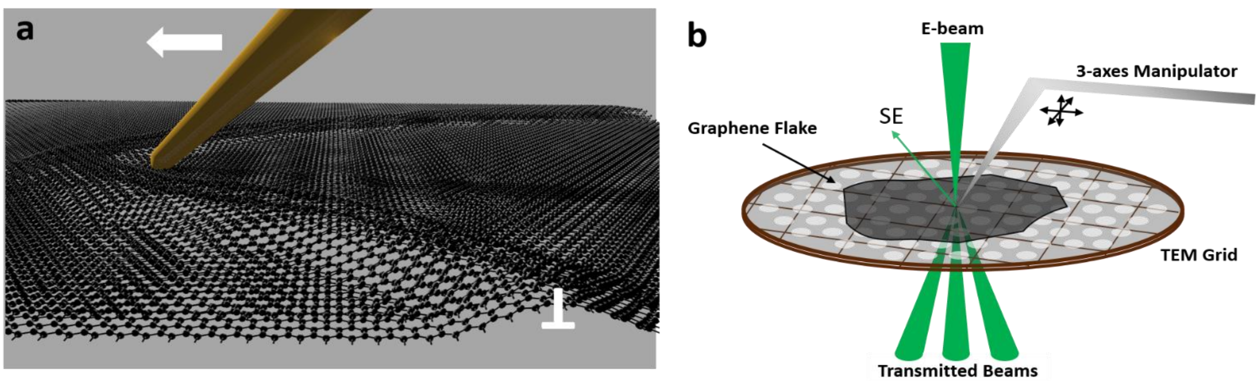

Figure 1: a) Artistic representation of the manipulation process: a metal tip is used to push around the defects which relax into topographic ripples. b) *In situ* tSEM setup: a Micromanipulator can be moved along three axes while an electron beam is scanned over the sample. The transmitted beams contain the crystallographic information used to make dislocations visible.

An exemplary manipulation is shown in figure 2 a-d, where a partial dislocation is moved upwards in a membrane. The dislocation reacts with other dislocations not affected by the direct manipulation and a switching reaction at threading dislocations is observed. This observation enables us to devise a topological switch purely based on dislocations with expected electronic functionality (figure 2 e-f). Additionally, fundamental dislocation phenomena are observed such as line tension and node formation, which have been extensively studied using Dark-field TEM, and HRTEM. Further, first experiments on bilayer graphene nanoribbons, containing a selected dislocation structure, by direct e-beam patterning have been made as a step towards device building.

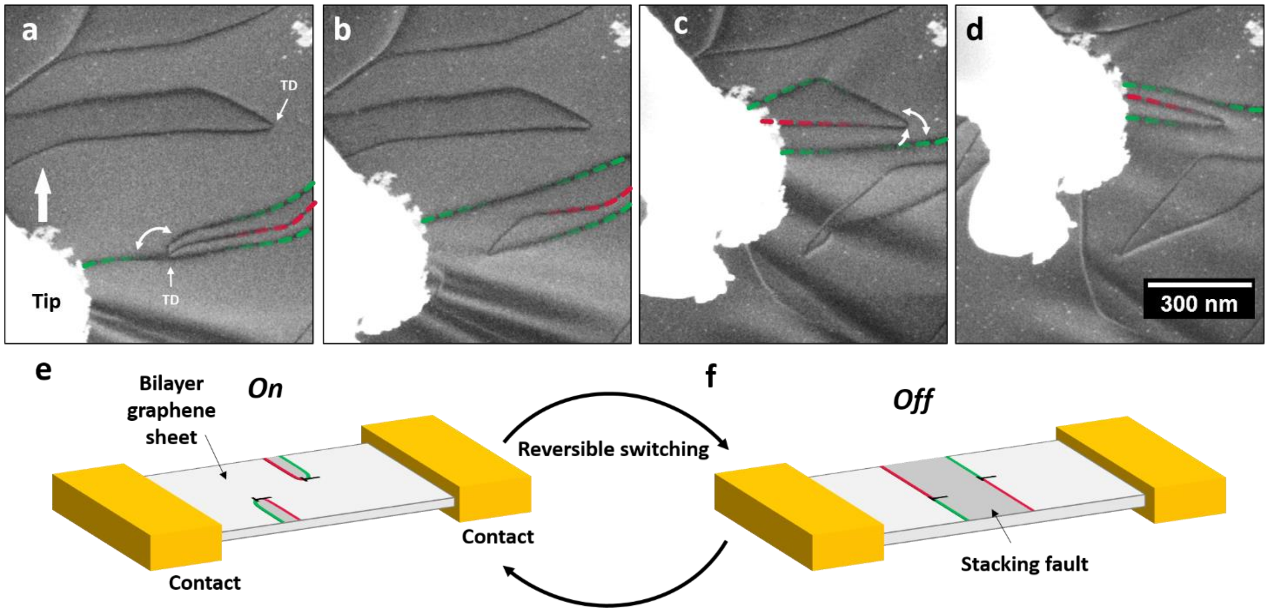

Figure 2: Exemplary dislocation Manipulation and topological switch. a-d) Frames from an *in situ* dark-field tSEM dislocation manipulation. Several dislocations are present in the graphene membrane, which can be directly controlled using a tip on a manipulator. Some Defects have the same burgers vector (indicated by color) and can therefore recombine at threading dislocations (TD). This novel switching reaction can be used to conceive a topological switch with expected functional properties (e-f).

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