Electronic Transport in Individual Carbon Nanotubes and Nanotube Networks by Scanning Probe Microscopy

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Progress in electronic devices based on 1D structures such as carbon nanotubes and semiconductor nanowires, as well as nanotube and nanowire networks requires development and understanding of quantitative tools for transport measurements at nanoscale dimensions. Scanning Probe Microscopy techniques provide a powerful set of techniques that allow real space imaging of transport phenomena with ~50-100 nm spatial and ~ 1 mV potential resolution, providing quantitative information on transport behavior within the network and even on the level of an individual nanotube.

Scanning Impedance Microscopy (SIM) studies of the conducting networks of single-walled carbon nanotubes within an insulating matrix allow frequency-dependent electrical transport in these systems to be accessed. The conductance of the composite is found to be limited by a small number of bundle-bundle and bundle-contact junctions [Fig. 1]. For high frequencies, the SIM phase distribution along the networks is governed by the capacitive interaction between the nanotubes and the substrate and can be modeled by a transmission line model. For low frequencies, the potential distribution can be determined after accounting for tip-surface capacitance variations at specific locations such as near electrodes. This constitutes a direct method to characterize and understand transport through networks formed by nanotube bundles in polymers, or more generally, nanorods in various matrices.

A combination of Scanning Gate Microscopy and SIM is shown to be capable of detecting atomic-scale defects in individual carbon nanotubes. The individual defects are visualized as a decrease in the current across the nanotube, since defects are depleted for tip voltages that are related to the local electronic structure of the defect. In SIM the local ac potential amplitude and phase are recorded; the defects are manifest as potential drops (back gate regime) or potential minima (tip gate regime). Here, a method for quantitative characterization of the electronic structure of individual defects from SGM and SIM results is presented. The interaction between a carbon nanotube and a point charge is studied using both atomistic first principles modeling and continuum electrostatic methods. The results are compared [Fig. 2] and extrapolated to real tip geometries. The combination of SIM and SGM thus allows determination of electronic properties of individual defects, providing real space information on atomic scale transport in these systems.

References:

[1] S.V. Kalinin, S. Jesse, J. Shin, A.P. Baddorf, M.A. Guillorn, and D.B. Geohegan, NanoTechnology, submitted
[2] V. Meunier, S.V. Kalinin, J. Shin, A.P. Baddorf, and R.J. Harrison, to be submitted
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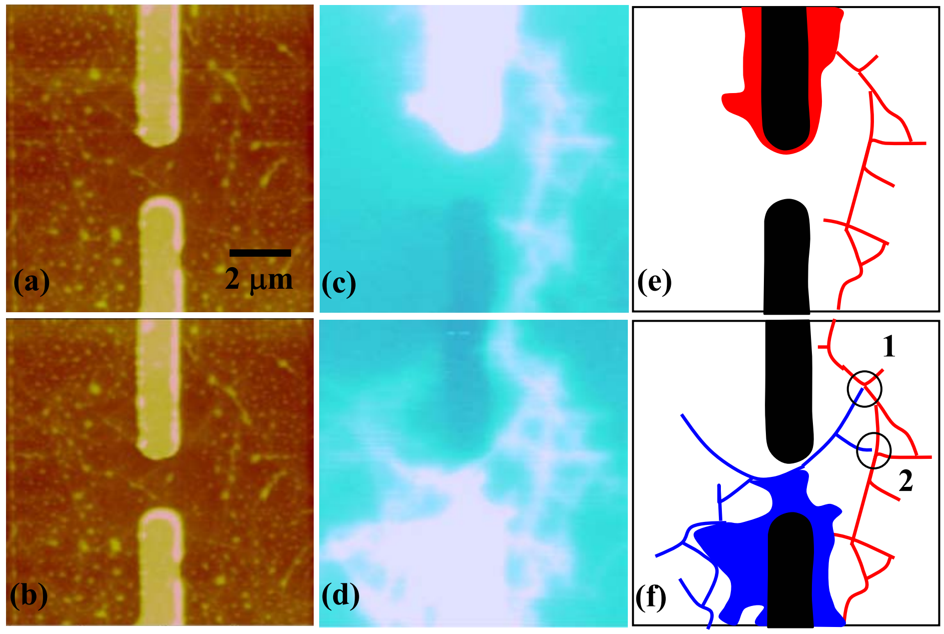
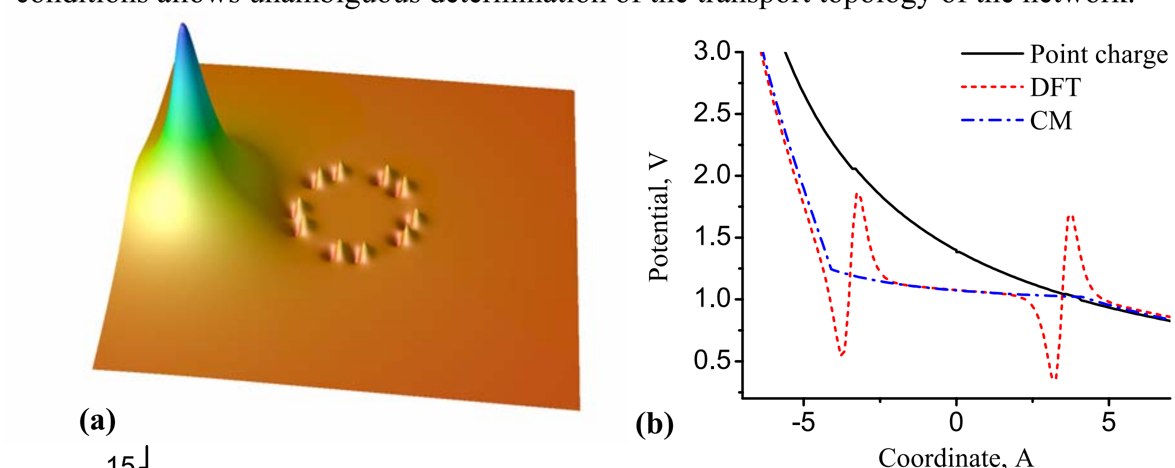


Figure 1. Surface topography (a,b) and SIM amplitude images (c,d) for top (a,c) and bottom (b,d) biased electrode configurations. Schematic potential distribution in the top (e) and bottom (f) biased network. Shown in red is the segment of the network biased through either contact, in blue the part of the network biased through the bottom contact only. 1 and 2 indicate the location of highly resistive junctions within the network. Direct comparison of the images under different bias conditions allows unambiguous determination of the transport topology of the network.



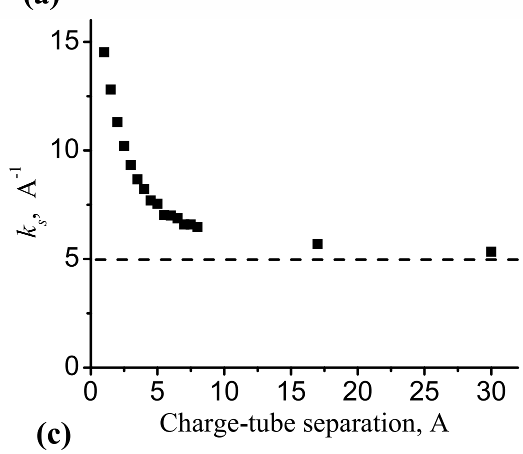


Figure 2. (a) 2D plot of potential distribution and (b) electrostatic potential across the (5,5) nanotube induced by point charge q = 1 e^- located at 10.4 A from the center of the nanotube. Shown are density functional theory (dot) and continuum theory (dash dot) results. (c) Distance dependence of effective inverse screening length k_s values.