Measurement of the quantum capacitance of interacting electrons in carbon nanotubes

Authors: S. Ilani*, L. A. K. Donev, M. Kindermann and P. L. McEuen

Nature physics, Vol. **2,** p867 (2006).

And

Quantum Capacitance Spectroscopy of Single Nanotube Molecules

Authors: Yuerui Lu, Ryan Tu, Xinran Wang, Yoshio Nishi and Hongjie Dai

http://xxx.lanl.gov/abs/0707.0171v1

Recommended and a commentary by Rafi de Picciotto, Bell Laboratories.

These two works report measurements of the capacitance between a carbon nanotube and a nearby gate. The two experiments are conducted with different device parameters, and as a result underline different electronic properties - revealed by the dependence of this capacitance on the charge density in these one dimensional (1D) conductors.

With such devices, the total capacitance, *C*, is related to the compressibility $\frac{\partial\mu}{\partial n}$, via:

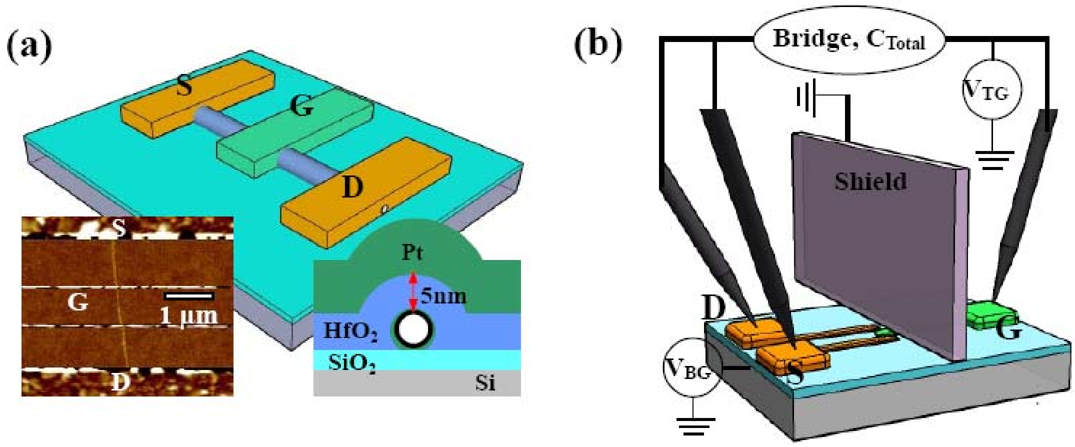
$$\frac{1}{C}=\frac{1}{C_g}+\frac{1}{e^2}\frac{\partial\mu}{\partial n},$$

where C_g is the classical geometrical capacitance. The compressibility term reflects the kinetic energy cost of adding charge, i.e. the finite density of states, and also correlation energy not captured in the classical electrostatic energy.

In the experiment by Yuerui et al., atomic layer deposition is used to deposit a 5nm thin layer of HfO_2 (an insulator with a dielectric constant as high as ε_r ~20) onto a nanotube, to serve as a gate dielectric. The large permittivity and the thinness of the layer work in concert to increase the geometrical part of the total capacitance. In fact the geometrical capacitance thus created is so large that the measured capacitance is dominated by the compressibility of the 1D liquid in the tube (see their figure 1). If the coulomb interactions between electrons is ignored, the compressibility simply reflects the density of states, and indeed the data is readily recognized as the van Hove singularity in the density of states occurring at the edge of the 1D sub-bands in the tube. This data therefore represents a beautiful manifestation of this unique 1D density of states.

The authors argue further that such sharp features in the measured capacitance are sensitive enough to the diameter and chirality of the tube so that the apparatus represents a tool for precise tube chemical identification (see their figure 3). On the other hand, it is well known that Coulomb interactions lead to significant modifications of the electronic properties of 1D conductors. One would therefore suspect that the compressibility of such Luttinger Liquids would differ from the non-interacting one, potentially hindering chemical identification. However, a large geometrical capacitance leads to efficient screening of the interactions and suppress such Luttinger Liquid effects – as is evident from the excellent agreement between the data and non-interacting models.

Still, the capacitance between a 1D wire and a gate may reveal more information than just the non-interacting density of states. To allow correlations to develop and affect the capacitance one would need to set the metallic gate back, away from the wire, to suppress its screening efficiency. This is exactly what was done in a preceding work by Ilani *et al.* This group performed the same experiment but with a thicker dielectric of smaller permittivity (10 nm of SiO_2 (ε_r ~3.9) in this case). Consequently, the compressibility correction to the total capacitance is smaller – with the capacitance largely dominated by the geometrical one. Importantly, this smaller yet measurable correction does not agree with a simple non-interacting model. This group found that a Hartree model underestimates the measured capacitance. This means that the model, accounting for the kinetic and approximating the potential energy, over estimates the total energy of the system. Correlations among the carriers, caused by the coulomb interactions, would lower the energy and therefore increase the total capacitance. Indeed, a Hartree-Fock model captures this correction and leads to a much better agreement between the data and theory, at least within the 1st sub-band (see their figure 5).



Quantum capacitors: A 5nm HfO2 dielectric separates a single wall carbon nanotube from a metallic gate. The setup includes careful shielding of the electric field to reduce stray capacitances. (adopted from Yuerui et al.)