Atomic Scale Electronic Imaging of Graphene Devices:
"Flood Gate" Effect Increases Tunneling Conductivity

In a collaboration between the MSD groups of Michael Crommie and Alex Zettl, scanning probe microscopy was used to measure the tunneling electrical conductivity in a sheet of graphene one atomic layer thick while the density of electrons in the sheet was varied. The group discovered a new "phonon floodgate" effect in which vibrations of the atoms in the sheet make it easier for electrons to enter, thus increasing its tunneling conductivity.

Crystalline graphite consists of stacked planes of sp^2 bonded carbon atoms. Graphene is a single atomic layer of graphite. Due to its simple two-dimensional structure, which resembles a hexagonal honeycomb, graphene has become a testing ground for condensed matter physicists. There is great excitement over its possible future applications in nanoscale devices because it exhibits a number of unique properties. For example, in classical Newtonian mechanics the energy of an object is proportional to the square of its momentum. This is also true for conduction electrons in most semiconductors. However, in graphene, the energy of the conduction electrons varies linearly with their momentum, leading to predictions of a number of novel nanometer-scale phenomena.

In order to study the microscopic origin of their electrical conduction properties, graphene sheets made in the laboratory of Alex Zettl were examined by scanning tunneling microscopy (STM) in the Crommie lab. A single sheet of graphene was placed on an insulating silica substrate. An electrode under the silica functioned as a "back gate" allowing control of the electron density in the graphene sheet (i.e., a negative gate voltage pushes electrons out of the sheet and a positive bias adds electrons). The "tunneling" of electrons from an STM tip brought very close to the top of the graphene sheet was measured as a function of both the tip-sample bias and the gate voltage. Although graphene is expected to be a "semi-metal" allowing tunneling of electrons into the sheet at zero sample bias, instead an energy-gap-like behavior was observed. Below the effective gap voltage very little tunneling was observed; above it, electron tunneling into the sheet was greatly enhanced. Moreover, the gap feature persisted over a wide range of graphene electron densities (gate voltages). This unexpected finding can be explained by an an "inelastic tunneling" mechanism, in which the jump that electrons make from the tip to the graphene is assisted by a particular out-of-plane lattice vibration of the carbon atoms. Above the energy of this vibration (the flood gate level), emission of a "phonon" (quantum of lattice vibration) during tunneling allows electrons from the tip to more easily enter the graphene, increasing the tunneling rate.

Most electronic devices used in high technology today (e.g. the transistors in integrated circuits) rely on the ability to change device properties via the application of a gate potential. Thus, understanding how graphene responds to a gate voltage at the nanoscale is very important. Since this phonon flood gate effect is strongly nonlinear, it could potentially be useful in future graphene nanodevices.

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Yuanbo Zhang, Victor W. Brar, Feng Wang, Caglar Girit, Yossi Yayon, Melissa Panlasigui, Alex Zettl, Michael F. Crommie, "Giant Phonon-induced Conductance in Scanning Tunneling Spectroscopy of Gate-tunable Graphene," *Nature Physics* **4**, 627 (2008).

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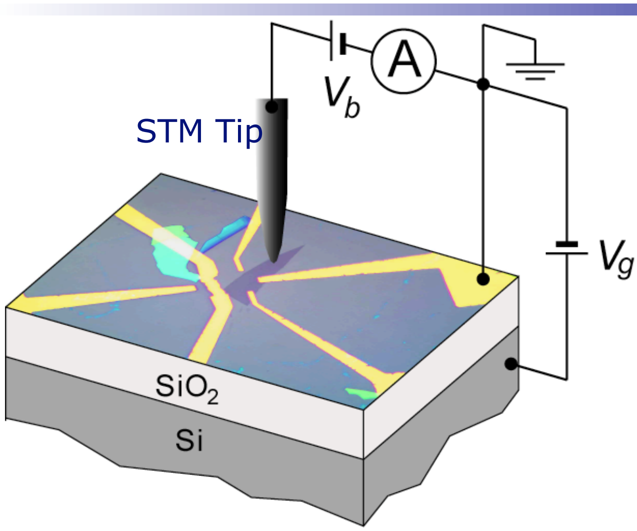
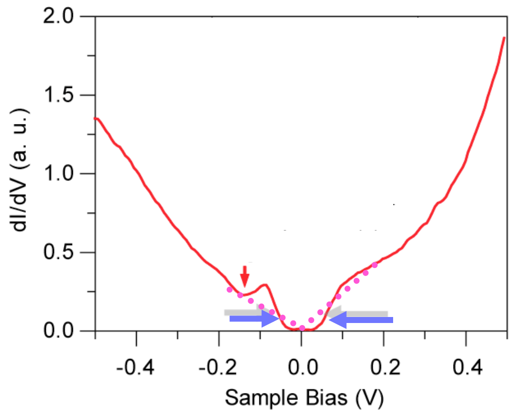
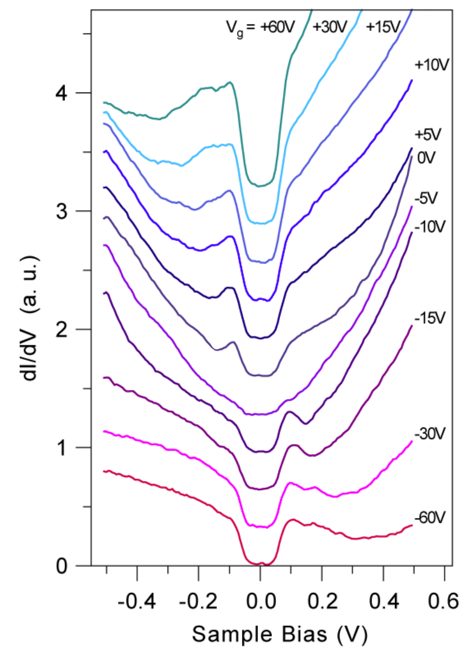


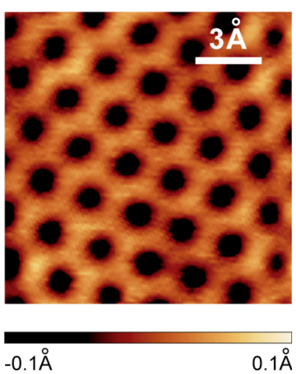
Scanning tunneling microscopy (above) of a single graphene sheet. *The circuits used to apply a gate potential (V_g) and to measure the tunneling current from the STM tip into the graphene are illustrated. The graphene honeycomb lattice can be easily resolved (below).*



Tunneling current into the graphene sheet at zero gate bias *as a function of sample bias. A “gap-like-feature” (between the blue arrows) in the tunneling current is observed. Gapless behavior (pink dotted line) is expected for a semimetal.*

The gap is independent of gate voltage (individual curves offset for clarity).





The gap is seen regardless of gate bias (figure at right, above) because it is due to phonon-assisted inelastic tunneling of electrons. At low sample bias levels the energy difference is below the critical threshold for a lattice vibration. No phonon can be produced, and tunneling is minimal. At higher sample bias (red arrow), above the "flood gate" level, the phonon can be produced, so conductivity is greatly enhanced.