

## Carbon Sheet Bandgap Engineering Reveals Semiconductor Possibilities

**Graphene**, because of its unusual electron properties, reduced dimensionality, and scale, has enormous potential for use in ultrafast electronic transistors. It exhibits high conductivity and an anomalous quantum Hall effect (a phenomenon exhibited by certain semiconductor devices at low temperatures and high magnetic fields). Among its novel properties, graphene's electrical charge carriers (electrons and holes) move through a solid with effectively zero mass and constant velocity, like photons. Graphene's intrinsically low scattering rate from defects implies the possibility of a new kind of electronics based on the manipulation of electrons as waves rather than particles. The primary technical difficulty has been controlling the transport of electrical charge carriers through the sheet. This area of research is known as bandgap engineering. While bandgap engineering is the basis of semiconductor technology, it is only now being applied to graphene. Using angle-resolved photoemission spectroscopy (ARPES) at ALS Beamline 7.0.1, a team of scientists from the ALS and Germany characterized the electronic band structure and successfully controlled the gap between valence and conduction bands in a bilayer of graphene thin films deposited on a substrate of silicon carbide. This was done by doping one sheet with adsorbed potassium atoms, creating an asymmetry between the two layers.

Graphene's unique electronic structure is characterized by conical valence and conduction bands that meet at a single point in momentum space (the Dirac crossing energy). The researchers demonstrated that through selective control of the carrier concentration in the graphene layers, the band structure can be easily tuned near the Dirac crossing. Similar control can be achieved in principle by varying the electric field across the bilayer film in an atomic-scale switching device.

If undoped, a bilayer of graphene sheets is considered a semimetal, a material in which the conduction and valence bands slightly overlap in energy. When the researchers first synthesized their bilayer graphene films onto the silicon carbide substrate, the graphene became a weak *n*-type semiconductor, having a slight excess of negatively charged electrons; the interface layer acquired an excess of conduction electrons from the substrate, creating a small bandgap.

Potassium atoms deposited onto the graphene donated their lone valence electrons to the graphene's surface layer, initially closing the bandgap. However, as the potassium deposition continued, the bandgap was reopened by the excess of electron charge-carriers on the graphene's surface layer. Progressive potassium deposition further enhanced the *n*-type doping.

These results demonstrate that by controlling the carrier density in a bilayer of graphene, the occupation of electronic states near the Fermi level ( $E_F$ ) and the magnitude of the gap between the valence band and conduction band can be manipulated. This control over the band structure suggests the potential application of bilayer graphene to switching functions in electronic devices with a thickness of only two atomic layers.

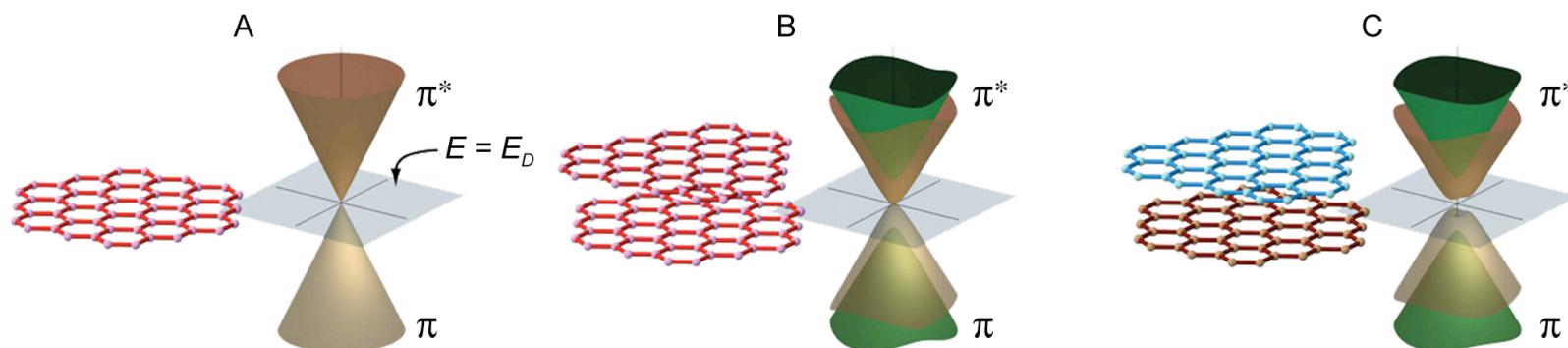
This experiment was a tour de force on multiple levels. In addition to characterizing and controlling the graphene bandgap, the researchers found the current capacity to be surprisingly high. At a temperature of 30 kelvin, cold enough to preclude any conduction through the substrate, they were able to pass 400 milliamperes through a macroscopic sample. This corresponded to a current of about 20 million amps per square centimeter, the same order of magnitude reported for single-walled carbon nanotubes and graphene multilayers.

The results of this experiment showcase ARPES and the techniques developed at Beamline 7.0.1. This ability to obtain detailed information about changes that occur on a small scale in momentum space, and which are induced by only a small, dispersed distribution of atoms, means that useful information can be obtained not only for electronic applications but also for chemical applications (such as sensors). The researchers are now focusing on combining this capability with future high-spatial-resolution photoemission in order to derive useful information from real-world devices.

## *Carbon Sheet Bandgap Engineering Reveals Semiconductor Possibilities*

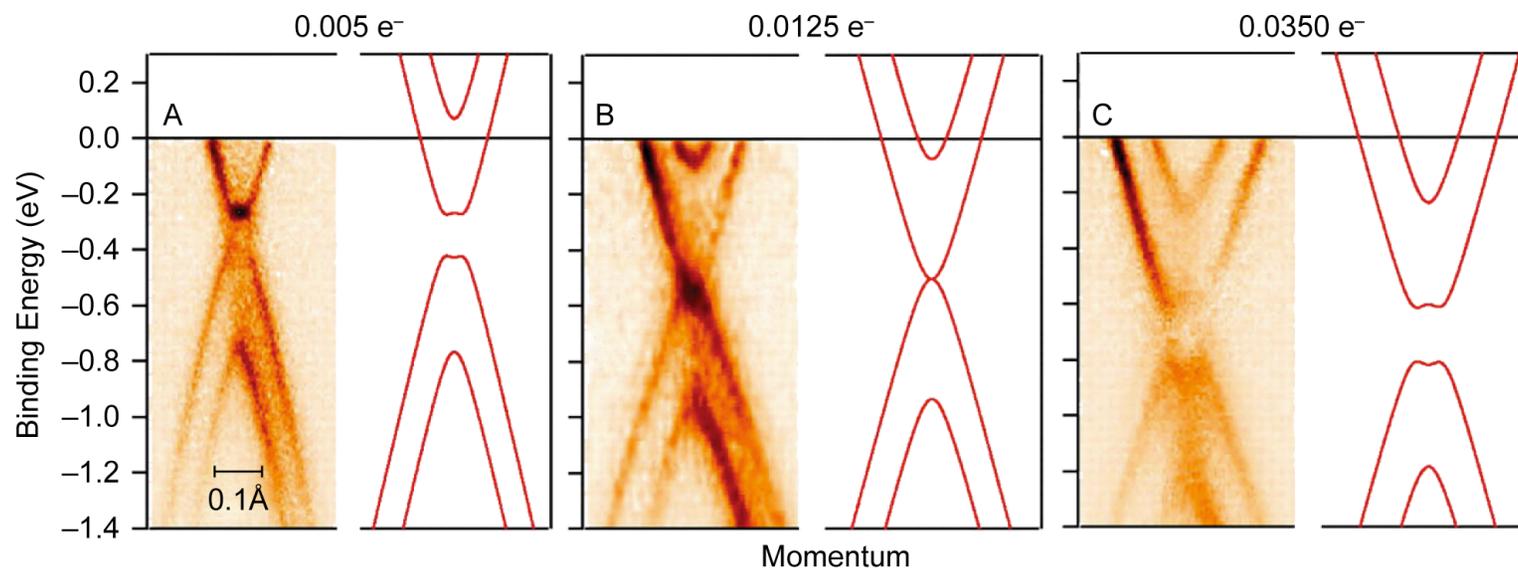
- **Graphene, a 2D sheet of hexagonally arranged carbon**
  - *Exhibits high conductivity*
  - *Has anomalous quantum Hall effect*
  - *Exhibits low scattering rate from defects*
  - *Electrons act more like photons than particles*
- **Using ARPES at ALS beamline 7.0.1**
  - *Bilayer graphene bandgap characterized and controlled*
  - *By doping one sheet with adsorbed potassium atoms*
  - *Creating asymmetry between two layers*
  - *Showing conical valence and conduction bands meet at Dirac crossing energy*
  - *Tuning band structure near the Dirac crossing*
  - *Manipulates magnitude of gap between valence and conduction bands*
- **Potential Application**
  - *Switching functions in atomic-scale electronic devices*

## Carbon Sheet Bandgap Engineering Reveals Semiconductor Possibilities



*Electronic structure of a single (A), symmetric double layer (B), and asymmetric double layer (C) of graphene. The energy bands depend only on in-plane momentum because the electrons are restricted to motion in a two-dimensional plane. The Dirac crossing points are at energy  $E_D$ .*

## Carbon Sheet Bandgap Engineering Reveals Semiconductor Possibilities



*Evolution of gap closing and reopening by changing the doping level by potassium adsorption. Experimental and theoretical bands (solid lines) (A) for an as-prepared graphene bilayer and (B and C) with progressive adsorption of potassium are shown. The number of doping electrons per unit cell, estimated from the relative size of the Fermi surface, is indicated at the top of each panel.*